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### Analysis of In-Situ Rock Joint Strength Using Digital Borehole Scanner Images

B.B. Thapa  
(Ph.D. Thesis)

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**Analysis of In-Situ Rock Joint Strength Using Digital Borehole Scanner Images**

**By**

**Bhaskar Bahadur Thapa**

**B.S. (Carnegie-Mellon University) 1985**

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**1994**

# **Analysis of In-Situ Rock Joint Strength Using Digital Borehole Scanner Images**

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**Bhaskar Bahadur Thapa**

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## **Abstract**

### **Analysis of In-Situ Rock Joint Strength Using Digital Borehole Scanner Images**

by

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Doctor of Philosophy in Engineering-Civil Engineering

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The availability of high resolution digital images of borehole walls using the Borehole Scanner System has made it possible to develop new methods of in-situ rock characterization. This thesis addresses particularly new approaches to the characterization of in-situ joint strength arising from surface roughness.

An image processing technique is used to extract the roughness profile from joints in the unrolled image of the borehole wall. A method for estimating in-situ Rengers envelopes using this data is presented along with results from using the method on joints in a borehole in porphyritic granite. Next, an analysis of the joint dilation angle anisotropy is described and applied to the porphyritic granite joints. The results indicate that the dilation angle of the joints studied are anisotropic at small scales and tend to reflect joint waviness as scale increases.

A procedure to unroll the opposing roughness profiles a joint to obtain a two dimensional sample is presented. The measurement of apertures during this process is

shown to produce an error which increases with the dip of the joint. The two dimensional sample of opposing profiles is used in a new kinematic analysis of the joint shear stress-shear deformation behavior. Examples of applying these methods on the porphyritic granite joints are presented.

The unrolled opposing profiles were used in a numerical simulation of a direct shear test using Discontinuous Deformation Analysis. Results were compared to laboratory test results using core samples containing the same joints. The simulated dilatancy and shear stress-shear deformation curves were close to the laboratory curves in the case of a joint in porphyritic granite.

Approved by: Richard E. Goodman, Professor of Civil Engineering

Richard E Goodman      August 8, 1994  
Signature                      Date

*Dedicated to my parents, Bhekh and Rita, for whom this achievement is a reflection of their lifelong series of endeavors and accomplishments, and to my dear wife, Sumira, with whom I share this first attainment of our new life together*

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## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Joint characterization**

Joints commonly render rock masses into discontinuous material with anisotropic, non-homogeneous, non-linear mechanical and hydraulic properties. Furthermore, the influence joints have on the mechanical and hydraulic behavior of the rockmass depends on a wide variety of specific joint characteristics. Detailed descriptions of such joint characteristics are given in Bieniawski (1989), Dershowitz and Einstein et. al. (1988) and Brekke and Howard (1972). These joint characteristics include origin mode, size, orientation, spacing, persistence, infilling, wall alteration and strength, aperture, surface roughness and intersections made with other joints. Mode of origin is a characteristic which refers to whether the joint developed as a tensile or shear fracture. Joint properties affected by the joint's surface roughness will reflect the mode of origin of the joint. The size of the joint in terms of a length or surface area can vary from millimeters to kilometers. Knowledge of the joint size is useful in determining the importance of a given joint for the scale of the problem being studied. Joint orientation and spacing define the geometric configuration of the joint system which is important in understanding the behavior of the overall rockmass. Joint persistence refers to the fraction of the total joint size not occupied by rock bridges. Persistence gives an idea of the deviation of joint behavior that may be expected from a joint with no rock bridges. Infilling is material deposited on the joint and often consists of clay minerals. Joint wall alteration occurs where fluid flow is present and can substantially alter the mechanical and hydraulic properties of the joint. Finally, the joint aperture is the distance separating opposing joint walls. Joint aperture and surface roughness

are fundamentally important for mechanical and hydraulic behavior as will be shown later.

Many studies have been done to study the relationships between joint characteristics and the mechanical and hydraulic behavior of joints or rock block systems defined by joints. The closure curve of opposing interlocking joint walls under normal compression has been found to be hyperbolic with initial aperture, joint wall rock strength and surface roughness being the main joint characteristics affecting closure behavior (Bandis et. al. 1983). Bandis et. al. (1983) also found the closure curve of dislocated joints to be best described by a semilogarithmic function. Patton (1966), Schneider (1976), and Barton and Choubey (1977) have investigated joint shear deformation behavior and found it to be controlled by the surface roughness, joint wall compressive strength and the residual friction angle of the joint wall. An alternate model of shear strength that also accounts for the strength of the joint asperities was presented by Ladanyi and Archambault (1970). Coupled hydromechanical behavior of joints can be studied using a modified form of Darcy's law where an equivalent smooth wall aperture is used instead of the true joint aperture (Makurat et. al., 1990). Bandis (1994) describes a model for estimating the equivalent smooth wall aperture assuming radial flow through one joint in an isolated borehole section during a pumping test. Barton et. al. (1985) describe a relationship between the equivalent smooth wall aperture, the true joint aperture and the Joint Roughness Coefficient. Barton (1974) describes the influence of joint infilling on shear deformation behavior in relation to two extreme cases: one where the infilling thickness is less than the roughness amplitude and the other where the infilling thickness is large enough to mask the effect of surface roughness during shear deformation. Barton and Bandis (1980) present results and recommendations from a study of the scale effects of joint characteristics on shear deformation



behavior. Construction of probabilistic three dimensional geometric models of the joint and rock block system based on joint orientation, trace lengths and spacings are described by Pointe (1994) and Dershowitz and Einstein et. al. (1988). The stability of a system of blocks delineated by joints has been rigorously shown by Block Theory to be controlled by joint orientation and strength (Goodman and Shi, 1985). The conclusions of Block Theory have also been validated through field studies (Hatzor, 1992). Long (1994) describes a technique to simulate fluid flow through fractured rock using a probabilistic characterization of the joint geometry. The basic relations that these various investigations have produced have made it possible to gain geologic insights. For instance, in structural geology studies, paleo stress field orientations and relative ages are inferred from regional joint orientations and cross-cutting relationships respectively ( Suppe, 1985). Geomorphologic studies of erosion through cliff retreat and mass wasting involve considerations related to joint genesis, weathering and strength (Selby, 1982).

## **1.2 Methods of joint characterization**

Accompanying the progress in understanding of the basic relationships between joint characteristics and mechanical and hydraulic joint behavior, have been improvements in methods of measuring and predicting the joint properties of concern. There are many complementary and competing techniques available for evaluating geometric, mechanical, fluid flow and geologic properties of joints. These methods can be broadly viewed as borehole based and surface based methods.

### **1.2.1 Borehole Methods**

Geophysical well logging methods measure some property of the borehole wall which, directly or indirectly, is used to evaluate joint characteristics. Goodman (1976) and Telford et. al. (1990) provide detailed descriptions of these

methods, which are only listed here. Electrical resistivity surveys are used to identify fracture locations using the lower resistivities of altered joint walls. The dipmeter enables estimation of joint orientation from its record of electrical resistivity on four microresistivity pads separated by 90 degrees. Caliper logs show joint locations in terms of increased borehole diameter. Goodman (1989) describes the flat jack, hydraulic fracturing and overcoring techniques of stress measurement. Seismic tomography is used to identify fractured zones in the rockmass between boreholes using correlations between higher fracture density with lower seismic wave velocities and higher attenuation (Tanimoto et. al., 1994). Pump tests and tracer injection tests conducted over packed off segments of adjacent boreholes are used to evaluate joint connectivity, transmissivity and hydraulic conductivity (Lee, 1982). Logging of oriented core is used to estimate joint orientation. The joint walls obtained from core samples are used in direct shear tests and measurement of joint surface roughness.

The borehole televiewer produces an image of the acoustic reflectivity of the borehole wall. This device consists of an acoustic transmitter-receiver unit that follows a spiral path as it is pulled up the borehole. Since the amplitude of the reflected acoustic wave will be lower along parts of the spiral path that fall on joints, the joints show up as dark areas in the televiewer image. The televiewer image is used to calculate orientations, locations and spacings of joints. Zemanek et. al. (1970) provide a detailed description of the televiewer.

Several optical instruments have been used to study joints in boreholes. The borehole camera takes color pictures of overlapping segments of a borehole wall. The camera points down the borehole towards a conical mirror that deflects the light reflecting off the borehole wall. Interpretation of the image is done by analyzing either a cylindrical reconstruction of the borehole wall or a flat donut shaped projection of the borehole wall (Trantina, A. and Cluff, L.S., 1963). The

orientation and location of joints can be obtained from the borehole camera. The borehole TV system uses a video camera that points down the borehole at a mirror inclined at 45 degrees which deflects light reflected from the borehole wall to the video camera (Briggs, 1964). Unlike the conical mirror of the borehole camera, the mirror in the borehole TV receives light reflected off only a portion of the borehole circumference. Adjacent portions of the borehole circumference can be obtained by rotating the mirror. The orientation and location of joints can be measured from a mosaic of adjacent borehole TV images. Finally, a periscope device called a stratoscope (Cluff, 1966) can be used to view the borehole wall at depths of less than 70 feet. A camera can also be attached to the eyepiece of the stratoscope.

### 1.2.2 Surface Methods

Joints can be mapped by observation of natural exposures, surface excavations and tunnel walls. Alternatively, photographs may be used instead of manual joint mapping for convenience. In the case of regional joint studies and inaccessible areas, aerial photographs or satellite images may be the only alternatives. The data in maps or photographs are analyzed for joint set orientations (Goodman, 1976), joint spacing distributions and joint trace length distributions (Priest and Hudson, 1976). In the case of mechanical stability problems, keyblocks can be identified directly from the joint map as specific polygons formed by intersecting joints (Shi and Goodman, 1989).

Joint strength can be measured by in-situ direct shear tests, laboratory direct shear and triaxial tests using joint samples from accessible surfaces (Goodman, 1976), push and pull tests (Barton et.al, 1990), field and laboratory tilt tests (Barton and Choubey, 1977), induced wedge tests (Thapa and Goodman, 1994), measurement of joint surface roughness (Fecker and Rengers, 1971),

and field block sliding tests. Snow (1970) describes photographic techniques of aperture measurement.

### **1.3 Limitations of existing joint characterization methods**

Even with the various capabilities acquired as a result of the advances in joint characterization described above, there remains a need for further development. Hudson (1994) has reviewed existing methods of joint characterization and finds many core sample based methods to be unsatisfactory, borehole camera based methods to be better and surface based methods to be mostly satisfactory. Given that many important joint and rockmass characterization tasks are done on sites where surface exposure is not available, there is at least a need for advances in borehole based joint characterization methods.

A major cause for the poor performance of core sample based methods is the disturbance of the sample caused during the drilling and recovery process. For instance, the use of oriented core for estimation of joint orientation can be misleading if the core recovery is poor (Goodman, 1976). Sample disturbance makes it difficult to assess in-situ properties such as infilling and wall strength. Weak material critical to the evaluation of rockmass properties in highly weathered or fault zones, are difficult to recover. Open joints may be damaged during overcoring and subsequent aperture measurements may not be accurate. Additionally, destressing effects make aperture measurements questionable, particularly when the measurements are made near the ground surface. Persistence is impossible to assess from a borehole and difficult to estimate from surface observations of trace lengths. Improvements in areas such as these can be expected to make significant improvements in understanding and predicting the mechanical and hydraulic behavior of joints and jointed rockmasses.

## 1.4 Objectives

Recently, a new instrument called the Borehole Scanner System (BSS) has become available. The BSS is an optical instrument that produces a digital unrolled image of the borehole wall. The BSS<sup>1</sup>, and a similar instrument called the Borehole Image Processing System<sup>2</sup> (BIPS) provide significant advantages over the existing borehole imaging instruments described earlier. As will be shown later, the advantages presented by the BSS makes it possible to develop a number of new approaches to rock and joint characterization. The research in this thesis addresses particularly new approaches to the characterization of in-situ joint strength arising from surface roughness. A means of extracting the joint roughness profile from BSS image is examined first. Subsequently, profile analysis for strength characterization in terms of the dilation angle is developed for single and opposing profiles. Next a method for assessing the anisotropy of joint strength is developed. The final topic of this thesis is a numerical simulation of joint shear deformation behavior using DDA and comparison to laboratory results.

To provide data for the investigations of this thesis, BSS field measurements were made on two 3.5 inch diameter boreholes at an underground powerhouse site in Japan. Each borehole was about 70 meters long. Core samples from the boreholes were available for laboratory direct shear testing. The results of this thesis are not site specific and may be used on any site where similar quality BSS data can be collected. Also, although the work described in this thesis is based on the BSS, the results are general and can be used with either system.

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<sup>1</sup>Developed by Core Corporation, 3-4-15-903 Mita, Minato-ku, Tokyo 108, Japan

<sup>2</sup>Developed by Raax Company, 1400 Hermann Drive, 4-C, Houston, TX 77004

The methods developed in this thesis were implemented in C language computer programs. Other than the programs for extracting the roughness profile, these programs are fully portable and can be run on any IBM compatible personal computer. The profile extraction routines are made to be a part of a larger image processing program.

## **CHAPTER 2**

### **THE BOREHOLE SCANNER SYSTEM**

#### **2.1 Description of the BSS and Field Use**

The BSS consists of a probe, depth encoder, winch, controller, TV monitor and a VTR unit as shown in Figure 2.1. The watertight probe houses a white light source and a magnetic compass<sup>1</sup> at the bottom. A mirror rotating at 3000 rpm sits directly above the lamp, and reflects light from the lamp onto the borehole wall through a glass window. The light reflected off the borehole wall is again reflected by another side of the same rotating mirror into a photoelectric transformer. The photoelectric transformer measures the intensity of the incoming light in the red, blue and green wavelength bands and converts the intensities into digital form. The digital data from the photoelectric transformer is passed to an azimuth gauge which marks the point in the data stream corresponding to north. The data then passes through an amplifier to the controller at the surface via a cable with a tensile strength of 900 lb/ft<sup>2</sup>. The entire borehole wall is scanned along a spiral path in this manner as the winch lowers the probe.

The depth encoder at the top of the borehole records the depth at which the probe is scanning as the probe is lowered into the borehole. The minimum depth increment the encoder can detect is 0.1 mm at present. The controller receives the depth data from the depth encoder in addition to the oriented borehole wall reflectance data. The combined depth and reflectance data is stored on a digital tape. Subsequently, the data are also recorded on a video

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<sup>1</sup> The magnetic compass is currently being replaced by a gyroscope to avoid problems in magnetic rocks.

tape and displayed as a scrolling unrolled image of the borehole wall on a TV monitor.

The BSS can be used to scan boreholes with diameters ranging from 66 mm to 150 mm. Currently, the BSS can be used to scan boreholes upto 1000 m. deep at a maximum rate of 72 meters per hour. The inclination of the boreholes may range from vertical to sub-vertical to horizontal. At present, any water in the borehole must be clear<sup>2</sup>.

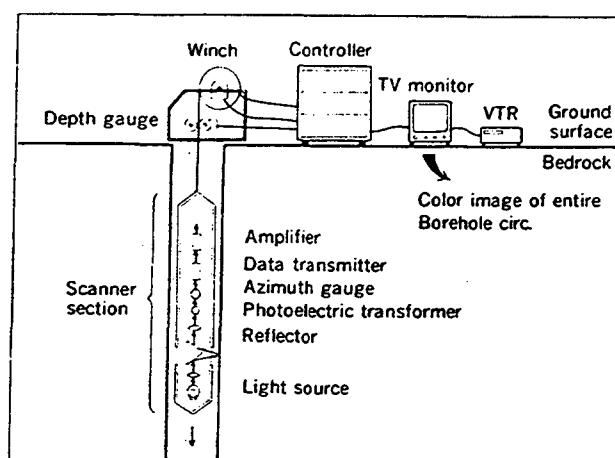


Figure 2.1: Schematic of the BSS

Prior to scanning, boreholes are flushed with clear water for about 48 hours and left undisturbed for about 24 hours to allow suspended particles to settle. This may not be possible in unstable terrain such as a landslide zone. In such cases, scanning is done immediately after drilling a few meters. The borehole is then cased and the drilling and scanning sequence repeated over successive depth intervals. In the case of horizontal or near horizontal boreholes, the scanner is first inserted into the borehole encased in a polythene pipe with just the scanning window of the probe protruding from the end of the pipe. The pipe is pulled back out as the winch pulls the probe back during the

<sup>2</sup> The manufacturer of the BSS, Core Corp., is planning to make another version of the equipment with an infrared light source. This change is expected to make it possible to scan boreholes with muddy water.

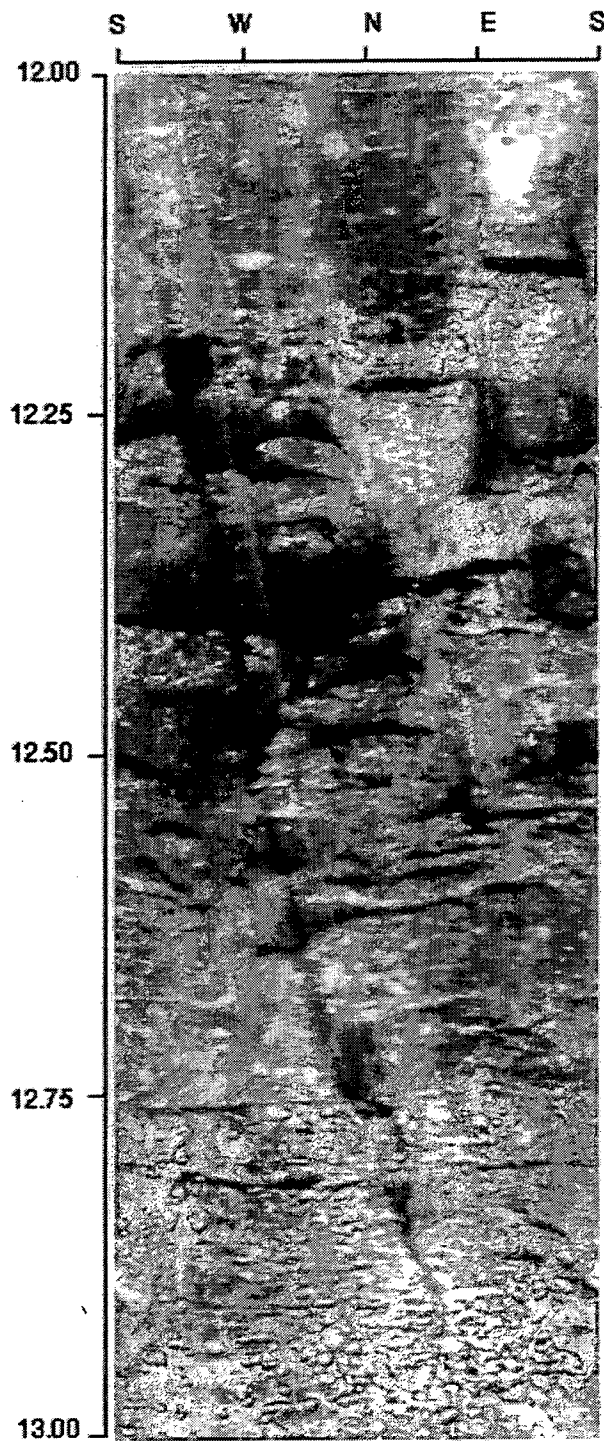


scanning. Use of the polythene pipe in this manner has an added advantage of protecting the scanner in case of borehole collapse. The disadvantage in using a pipe is the irregularity in the scanning path caused by occasional departures from a steady withdrawal rate of the pipe.

It is convenient to have access to the site by van since the winch and generator are difficult to carry long distances by hand. On difficult slopes, a crane may be needed to lower the winch and generator to the borehole. Two people are usually sufficient to perform the scanning on vertical boreholes--more people are needed to assist in the case of horizontal boreholes. The TV monitor is always watched during scanning to enable quick response in case of a borehole collapse.

## **2.2 Description of BSS Data**

One complete revolution of the probe's mirror picks up reflectance from all of the contiguous segments on the borehole wall at the same depth. The contiguous segments along the periphery of the borehole wall are discretized into a line of 1000 data points covering reflectance from equal angular intervals. A data point in each such line is a three dimensional vector defining the reflectance intensity, on a scale of 0 to 255, in the red, green and blue (RGB) wavelength bands. The location of the borehole wall segment represented by each such point is defined by the depth at which the point was scanned and the rotation sequence number (1-1000), which specifies the azimuth of the data point with respect to north. Thus the entire borehole wall is represented by lines of RGB data points at successive depths. A true color unrolled image of the borehole wall can be obtained by combining the RGB components of each data point on a computer. Each data point is represented by one pixel on a computer display of the borehole wall. Figure 2.2 shows a typical image obtained from BSS data by this process.



**Figure 2.2: Unrolled image of borehole wall**

The vertical resolution of the BSS data depends on the rate at which the probe is lowered into the borehole. This rate can be controlled from the winch. The maximum vertical resolution of 0.1 mm requires a slow lowering rate while a faster rate may be more desirable if fine detail is not important. The resolution along the periphery of the borehole wall depends on the borehole size. An 89 mm diameter borehole will have a horizontal resolution of 0.28 mm.

With three numbers assigned to each data point at high resolution, the BSS produces a large volume of data. To facilitate data manipulation, only 500 of the available 1000 horizontal points are transferred to the data analysis computer system. In this form, one meter of BSS data typically requires about 3 MB of storage space. A rewriteable magnetic-optical disk with a capacity of about 300 MB per side is used for BSS data storage and manipulation on a personal computer.

## **2.3 Advantages of the BSS**

The BSS offers advantages over existing borehole wall imaging techniques and presents new opportunities to analyze rock mass properties in-situ.

### **2.3.1 Advantages over existing imaging methods**

The horizontal view of the borehole wall produced by the BSS is easier to analyze and visualize than the conically projected view produced by the borehole camera. The BSS shares this advantage over the borehole camera with the borehole TV and televiewer. Unlike the borehole TV however, the scanning mode of operation utilized by the BSS and the televiewer results in far more efficient data collection. While the BSS scanning gathers an unrolled image of the borehole wall at a rate of 72 meters per hour, the borehole TV works at a rate of 1-2 meters per hour. This is because the borehole TV has to be manually rotated through successive 40 degree intervals at each depth increment.

Furthermore, while the unrolled image of the borehole wall collected by the BSS is displayed in real time, the borehole TV images of segments of the borehole wall have to be manually spliced together afterwards.

The BSS has several advantages over the televiwer. First, the optical reflectance mapped by the BSS produces an image with more geologic information, since the BSS captures lithological and fracture details, while the acoustic reflectance from the televiwer provides no lithologic data. Next, the resolution of the televiwer is considerably poorer than optical tools because the wavelength of sound used in the televiwer is about 1000 times larger than the wavelength of visible light (Zemanek et. al., 1970). Zemanek et. al. (1970) estimate that the televiwer will have a resolution of 0.79 mm under ideal borehole conditions. Barton (1988) reports a typical resolution of the televiwer to be a few millimeters horizontally and one centimeter vertically in a 12 inch borehole. The BSS would produce data with a horizontal resolution of 0.95 mm and vertical resolution of 0.1 mm from the same 12 inch borehole. Unlike the televiwer whose operation requires the borehole to be filled with some fluid, the BSS will work in gas filled boreholes. This difference between the two instruments is important for non-vertical boreholes. An advantage of the televiwer is that the fluid in the borehole need not be clear as long as it is homogeneous. However, the quality and resolution of the televiwer image is reduced when operating in drilling mud.

The availability of the BSS data in digital format provides flexibility for data manipulation and analysis on a computer. This feature of BSS data is a significant improvement over televiwer logs which are usually constructed from Polaroid photographs of successive displays of acoustic reflectivity on a oscilloscope screen. A system to digitize such televiwer logs has recently been developed by Barton (1988).

### 2.3.2 New possibilities for in-situ characterization

The availability of the high resolution true color digital BSS data for computer based analysis makes it feasible to extract several in-situ rock properties for the first time. The BSS data also increases the efficiency at which joint orientations and apertures can be measured compared with other methods. Tanimoto et. al. (1992) describe how the BSS data can be analyzed for joint orientations and apertures at a rate of 10 - 50 meters a day compared to 1 - 2 meters a day in the case of borehole TV data.

The texture of the rock sampled by the BSS image can be quantified using a number of parameters. Fabbri (1984) describes image processing techniques applied to thin section images to measure grain size distributions, interparticle distances, grain circumference, cross-sectional areas of grains, grain orientations and porosity. Although BSS images do not have the resolution of thin section images, similar image processing and interpretation techniques can be developed for analyzing the borehole wall texture. Parameters describing larger textural features of interest can also be measured. Tang and Quek (1986) describe a Bayesian method for estimating boulder size distributions and volumetric proportions from borehole logs for construction planning. A similar approach can be used with BSS data to estimate these parameters. These boulder parameters are also of interest to geomorphologists studying the size and occurrence time of paleo floods. Recent work (Lindquist, 1994) shows the strength of melange is a function of the volumetric proportion occupied by blocks. As with the boulders, the BSS data can be used to estimate the proportion of blocks in a melange rockmass.

The three dimensional vector defining the color of each pixel in the BSS image makes it possible to identify regions of special interest. One example of such a region is a mineral grain or group of minerals. Feldspar for instance, may

have RGB reflectance intensities in the ranges 245-250, 250-255 and 240-255 respectively. A computer program can locate all feldspar crystals by isolating all pixels having RGB values in that range. More generally, a region growing image processing algorithm can be used to find all regions in the image having the same RGB values as a region defined by the user with a mouse. This approach to mineral identification requires user RGB value specification of the mineral of interest by observation of the BSS image and comparison with core samples when possible. A more general approach would utilize a predetermined library (Hunt and Salisbury, 1970) of the spectral reflectance characteristics of minerals. However, such spectral signatures used to uniquely identify minerals and rocks (Siegal and Gullipse, 1980) require many bands of reflectance data in the visible and near-infrared wavelengths. The currently available BSS does not provide such data. In addition to the petrologic analysis that would be made possible by mineralogy identification, knowledge of the minerals on joint walls would provide information on the basic friction angle of the joints intersected by the borehole.

Another region of interest in the BSS image is a weathering zone near the surface, fault or a joint. The RGB characteristics of a known conductive joint can be used in a region growing program to locate other possibly conducting joints in the same rocktype assuming joint wall alteration will be similar. Joints that are potentially troublesome from a mechanical point of view, such as those coated with chlorite and serpentinite or those filled with swelling clay, can also be located using a reference joint.

Statistical simulations of rockmass jointing are important for mechanical and fluid flow problems (Einstein, 1993). Such simulations typically involve numerous assumptions regarding distribution types, joint shapes and joint extents. The unrolled BSS borehole image provides a way to verify, update or calibrate the simulation model assumptions and parameters. For example, the

persistence of joints may be estimated through a trial and error process of assuming a set of values, making predictions for an adjacent borehole, comparing the prediction to the BSS data in that borehole and revising the assumed prediction so as to reduce discrepancies. BSS data from a reference borehole may be used to obtain the other parameters of the jointing model. The goodness of fit of a given simulation to the BSS data may be judged by the percentage of pixels in the simulation that are the same as in the BSS data.

Edge extraction image processing techniques can be applied to the BSS image to find the roughness profile of joints. The roughness profile is a fundamental joint feature and can be analyzed for a number of parameters. One such parameter is the joint dilation angle. The joint shear strength is completely defined by the dilation angle and the basic friction angle referred to earlier. The opposing in-situ joint profiles obtainable from the BSS data makes it possible to extend the existing method of deriving the dilation angle from roughness profiles which is applicable to perfectly mated joints only. Once dilation angles have been found for all joints in the various boreholes at a site, a spatial analysis of the variation of strength on different joint sets may be performed. For example, contours of joint strength would provide a quick way to assess weak zones.

The dilation angle derived from BSS data can be analyzed for anisotropy. Strength anisotropy can have a significant influence on deformations in jointed rock where block geometry constrains movement to certain kinematically feasible directions only. The BSS data provides the first opportunity to study this parameter in-situ.

After obtaining roughness profiles of opposing walls of a joint, the aperture along the entire joint sample can be obtained as the width of the opening separating the two sides. Aperture distributions can be compiled for various joint sets in this way. The data also enables a study of the relationship

between joint roughness and aperture, which may be of interest in fluid flow research. Additionally, the correlation of roughness profiles on opposing sides may be studied in-situ just as it is done using core samples (Brown, et. al. 1986).

Parts or all of the opposing joint roughness profiles can be unrolled into a two dimensional sample of the joint surface. The unrolled samples can then be used to simulate a laboratory direct shear test using a method such as Discontinuous Deformation Analysis (DDA) (Shi, 1985). In-situ shear deformation characteristics of the joints can be studied in this way.

Fourier transforms of in-situ joint roughness profiles may yield important information regarding joint genesis and subsequent alteration. Comparison of the power spectra of the roughness profile with the power spectra of the image of the joint wall can be used to see if the roughness profile reflects the grain size distribution of the rock wall. For instance, the power spectra of a sandstone joint wall composed of the same grain size would show a peak at the wavelength corresponding to the grain size. The power spectra of a purely tensile joint in this rock would also show a peak at the wavelength corresponding to the grain size. On the other hand, if joint alteration had significantly altered the roughness profile of the joint subsequent to its genesis, the power spectra of the roughness profile would show different peaks.

The fourier transform of the joint roughness profile can be used for other purposes as well. The slope of the power spectra can be used to estimate the fractal dimension of the joint surface roughness (Brown et. al. 1985). Subsequently, the fractal dimension can be used to simulate three dimensional models of the opposing joint surfaces. The fractal dimension or the moment (Tanimoto, et. al. 1994) may also be used to correlate joints across boreholes or to make joint membership assignments together with orientation. Tanimoto et. al. (1994) also show that the moment of the power spectra shows a strong



correlation to the Joint Roughness Coefficient (JRC) (Barton and Choubey, 1977). Utilizing this correlation, the BSS data can be used to estimate in-situ JRC values.

The BSS data may also be used for deformation analysis. Borchers et. al. (1993) report an analysis of fault offset made using BIPS data. Deformation analysis using BSS data may be very helpful in identifying the mode of failure in certain cases. For example, Ke et. al. (1994) describe a slope where it was difficult to decide if failure was occurring by sliding or toppling. Identification of a wedge shaped aperture distributions on tensile cracks would strongly suggest a toppling failure in this case. BSS data may also be useful in structural geology strain analysis to compile regional deformation patterns. Such assessments of regional deformation are used to interpret crustal movement and tectonic evolution (Ramsay and Huber, 1983).

## **CHAPTER 3**

### **ROUGHNESS PROFILE EXTRACTION**

#### **3.1 Hardware and Software**

The personal computer (PC) and graphics workstation as well as the software on them used in the roughness extraction process are described in this section.

##### **3.1.1 PC environment**

A specially configured PC with two screens, a special graphics adapter board, an external magnteo-optical (MO) disk drive and an external 8 mm tape drive is used to process the raw BSS data stored on a 8mm digital tape by the controller during field operation. All of the software used to process the BSS data with the PC was developed by Core Corp. Preprocessor utilities are used to transfer the raw data from digital tapes to rewritable MO disks. The data transfer utilities divide the raw data into files containing the data for successive one meter intervals. From the original data, which has 1000 pixels on each scanline, the data transfer utilities produce three files with 500, 100 and 10 pixels per scanline for every meter interval. This reduction of the raw data is done to suit the needs of the main analysis program and may be bypassed if desired.

The main analysis program, called Expert, reads the three files for each meter of the borehole and produces three types of displays of the unrolled borehole wall. The 10 pixel wide file is used to display the entire borehole so the user can select an interval of interest for more detailed analysis. The 50 pixel wide file is used to display a more detailed view of the meter of interest for user selection of a portion of the image within the meter for detailed analysis. Finally, the 500 pixel wide file is used for a detailed display from which the user interactively analyzes joint orientation and aperture. The joint orientation routine

simulates a sine curve using three user defined points lying on the joint. Another routine calculates an average aperture from the vertical distance between pairs of user defined points on the upper and lower joint walls. Expert also has several image processing routines that can be used to produce monochrome displays and RGB histograms, filter out noise and enhance the image. One example of how these image processing features can be used is the correction made on unusually dark images to uniformly increase brightness. A rotating cylindrical view of the borehole wall may also be seen using Expert.

Postprocessor routines are used to produce hardcopies of the BSS data and joint analysis results on a color laser printer with a 500 dpi capability. The results of joint analysis printed out are a joint trace map of the borehole wall, rose diagram of joint orientations and an equal area contour plot of joint densities. The trace map gives the strike and dip of joints, an average aperture for each joint and comments about the joint type.

For this thesis, the Expert program was used only to analyze joint orientations. Expert does not have the image processing tools needed to extract the roughness profile. Further development of Expert for roughness profile extraction on the PC was inconvenient since the PC works in Japanese, and is incompatible with the IBM PC. The 500 pixel wide data files were transferred to a graphics workstation for further analysis. It would have been desirable to work with the 1000 pixel files but these were not available at the time the work was done. However, the methods developed in this thesis are independent of the file size and future work can utilize 1000 pixel files.

### 3.1.2 AVS on a Graphics Workstation

The 500 pixel wide BSS data files were transferred from the NEC PC MO disk to the disk drive of a graphics workstation through a network file transfer utility. A utility program was written to convert the BSS data to a format readable

by a program called Application Visualization System (AVS). AVS<sup>1</sup> is a general purpose image processing and graphic visualization program. AVS was selected for use because it has a large library of image processing and three dimensional geometrical visualization modules. Also, AVS allows users to write their own modules, if the AVS library is not sufficient. A visual programming feature, called the network editor, in AVS makes it possible for the user to combine self-written and library modules to produce networks designed for specific tasks.

The AVS library modules were not sufficient to extract joint roughness profiles. Thus, additional custom modules had to be written and combined with the AVS modules to implement the thresholding edge extraction method described below. However, for geometric visualization of a cylindrical projection of the BSS image, the AVS modules were more than adequate. AVS allows the user to view such projections from any angle and to view plane slices made through the projection.

### **3.2 Review of edge extraction image processing techniques**

Digital image processing methods are used to enhance images for human perception and to analyze scenes for autonomous machine perception (Gonzalez and Woods, 1992). These methods have found applications in medicine, geography, archeology, physics, astronomy, biology, nuclear medicine, law enforcement and defense. Only a small subset of these methods relating to edge extraction is of interest in defining the roughness profile of joints. They are described below.

#### **3.2.1 General concepts**

In image analysis, segmentation methods are used to extract edges and other features of interest from an image. These methods divide the image into

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<sup>1</sup> Produced by Advanced Visual Systems, Inc., 300 Fifth Ave., Waltham, MA 02154

constituent segments based on two properties of intensity values: discontinuity and similarity (Gonzalez and Woods, 1992).

In monochrome images, a discontinuity can be detected based on a sharp change in gray-level intensity. Figure 3.1 illustrates one way of detecting such a discontinuity using derivative operators. In Figure 3.1, the location of discontinuities separating the light stripe from the dark background, and visa versa, are graphically represented by intensity changes and maxima and minima of the first and second derivatives of the intensity function. The intensity is shown to change smoothly between the light and dark stripes because digital images are slightly blurred from sampling (Gonzalez and Woods, 1992). The gray-level or intensity in monochrome images ranges from 0 (black) to 255 (white).

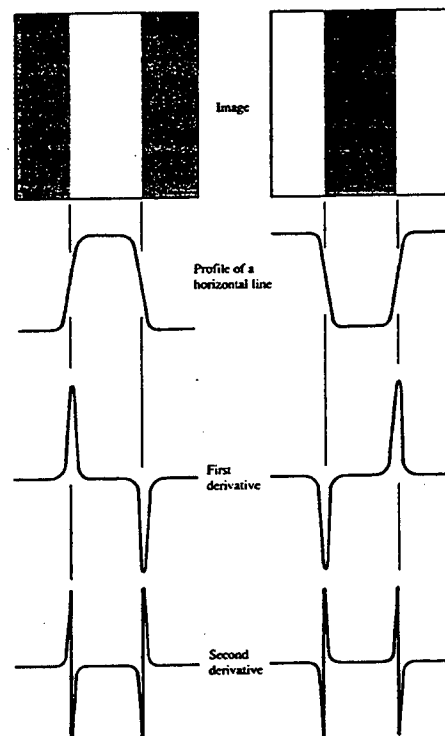


Figure 3.1: Discontinuity detection in images (after Gonzalez and Woods, 1992)

Similarity of gray-level intensities of a given feature in a monochrome images is the other major image property used in segmentation. Figure 3.2 shows a histogram of gray-level values for an image where the feature and background occupy two distinct ranges of intensity separated by a threshold value of  $T$ . In this case, the threshold value of  $T$  can be used to segment the image into the feature of interest and the background.

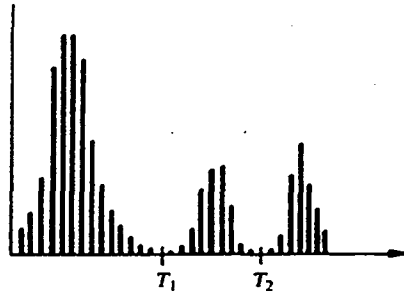


Figure 3.2: Segmentation using thresholding (after Gonzalez and Woods, 1992)

### 3.2.2 Thresholding method of profile extraction

All of the profile extraction processing is done on a monochrome transform of the BSS image. The roughness profile is extracted from the BSS image in four steps. The first step involves thresholding of the original image  $f(x,y)$  between two thresholds  $T_1$  and  $T_2$  to produce a binary image  $g(x,y)$  such that

$$g(x,y) = \begin{cases} 255 & \text{if } T_1 < f(x,y) \leq T_2 \\ 0 & \text{otherwise} \end{cases} \quad (3.1)$$

In Eqn. (3.1), the coordinates  $(x,y)$  refer to the row and column number of each pixel. The thresholds  $T_1$  and  $T_2$  are chosen so that in the binary image  $g(x,y)$ , all pixels falling inside the joint aperture are white while the pixels outside the aperture on the rock wall, are black. To accomplish this segmentation, the selection of  $T_1$  and  $T_2$  has to be made so as to cover only the dark range of intensities of the pixels in the aperture region between opposing joint walls.  $T_1$

and  $T_2$  can be determined from a histogram of the image intensities (as in Figure 3.2) or by probing the image with a mouse on a screen display of the image. The value of  $T_1$  can usually be set to zero. Figure 3.3 illustrates the application of the thresholding operation on a monochrome image.

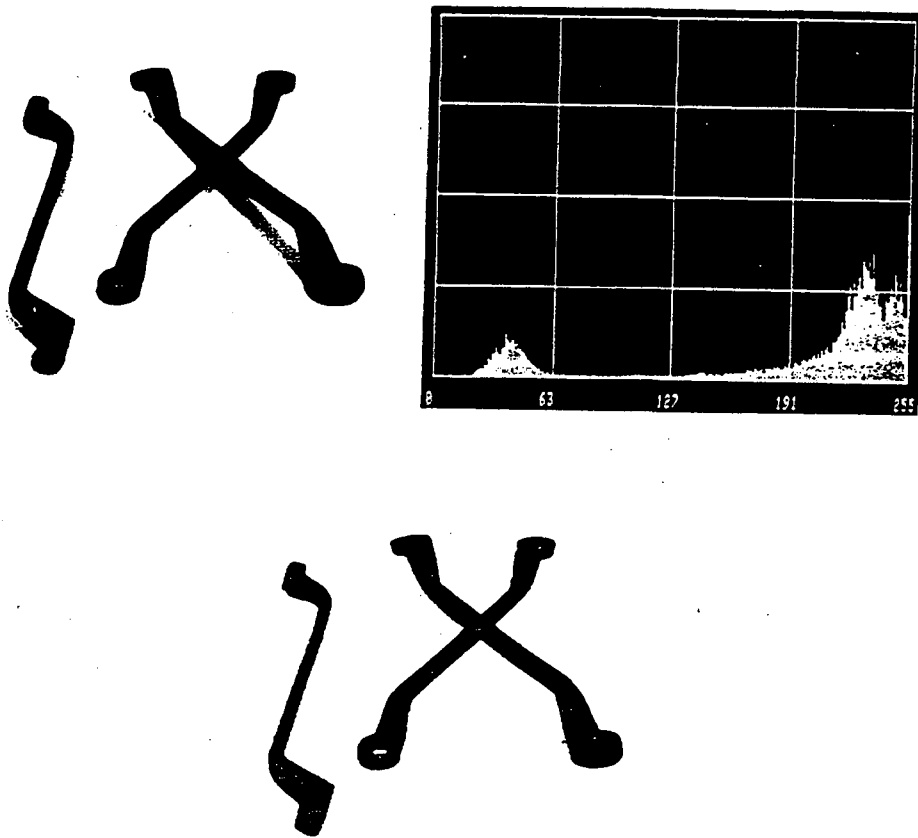


Figure 3.3: Illustration of thresholding (after Gonzalez and Woods, 1992)

After obtaining the binary image  $g(x,y)$ , the pixels on the roughness profile are isolated by detecting the discontinuity separating the rock wall from the joint aperture region. No differential operators are needed to detect the discontinuity in the binary image. Instead, the roughness profile pixels are isolated by using

the fact that only pixels on the profile and pixels in the aperture region will have at least one white adjacent pixel in the binary image. The pixels on the profile and those in the aperture region can be further distinguished by the fact the profile pixels in the binary image will be black while the pixels in the aperture region will be white. Only the pixels on the rock wall qualify as points on the roughness profile. These rules are applied on the binary image  $g(x,y)$  to produce another binary image  $h(x,y)$  in which pixels on the roughness profile have an intensity of zero and all other pixels have intensities of 255.

The next step involves using a pixel connectivity routine to produce an ASCII file listing of consecutive roughness profile pixel image coordinates. The connectivity routine begins at the first pixel on the profile and searches for the next pixel on the profile until no further connected pixels can be found. The center pixel in the 3X3 pixel box of Figure 3.4 is a pixel on the roughness profile and the adjacent pixels are candidate consecutive profile points. The numbers in the adjacent cells identify the cell. The search sequence for the upper profile is 2,3,6,8,9 and the search sequence for the lower profile is 8,9,6,3,2. The first adjacent pixel with an intensity of zero is identified as the next profile point. That point then becomes the center pixel in Figure 3.4 and the search is repeated.

|   |     |   |
|---|-----|---|
| 1 | 2   | 3 |
| 4 | X,Y | 6 |
| 7 | 8   | 9 |

Figure 3.4: Pixel connectivity search sequence

The final step in the profile extraction procedure is a transformation of coordinates. The ASCII file produced by the connectivity routine contains profile points in AVS (x,y) image coordinates. A utility program was written to substitute



borehole coordinates of rotation number and depth for the image coordinates by comparison to the original BSS image.

### 3.3 Implementation of the Thresholding method in AVS

The thresholding method described above was implemented in three AVS networks. These networks and examples of their use on BSS data are presented below. All three networks are used on a single joint in succession. An image of the example joint prior to analysis is shown in Figure 3.6.

#### 3.3.1 Threshold network

The thresholding operation only works on images where there is a clear and constant intensity threshold separating the joint wall and aperture region. Initial attempts to use the thresholding operation on the entire joint were unsuccessful because the upper threshold limit was not constant over the entire joint. The upper threshold limit is only constant over small regions of the joint where the aperture and lighting are more or less uniform. This situation made it necessary to implement the thresholding operation in a way that allowed the user to work over small regions of the joint and compile the results at the end.

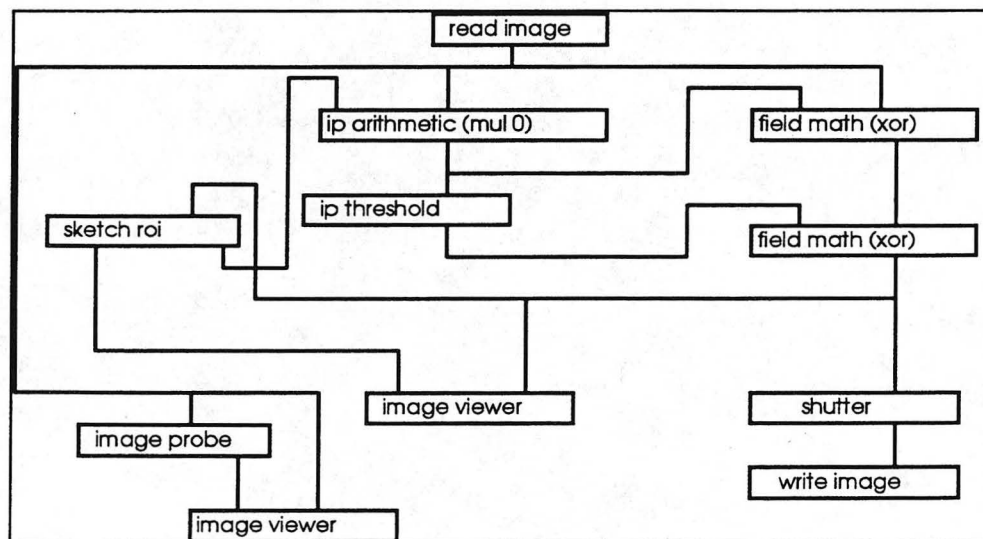


Figure 3.5: Threshold AVS network

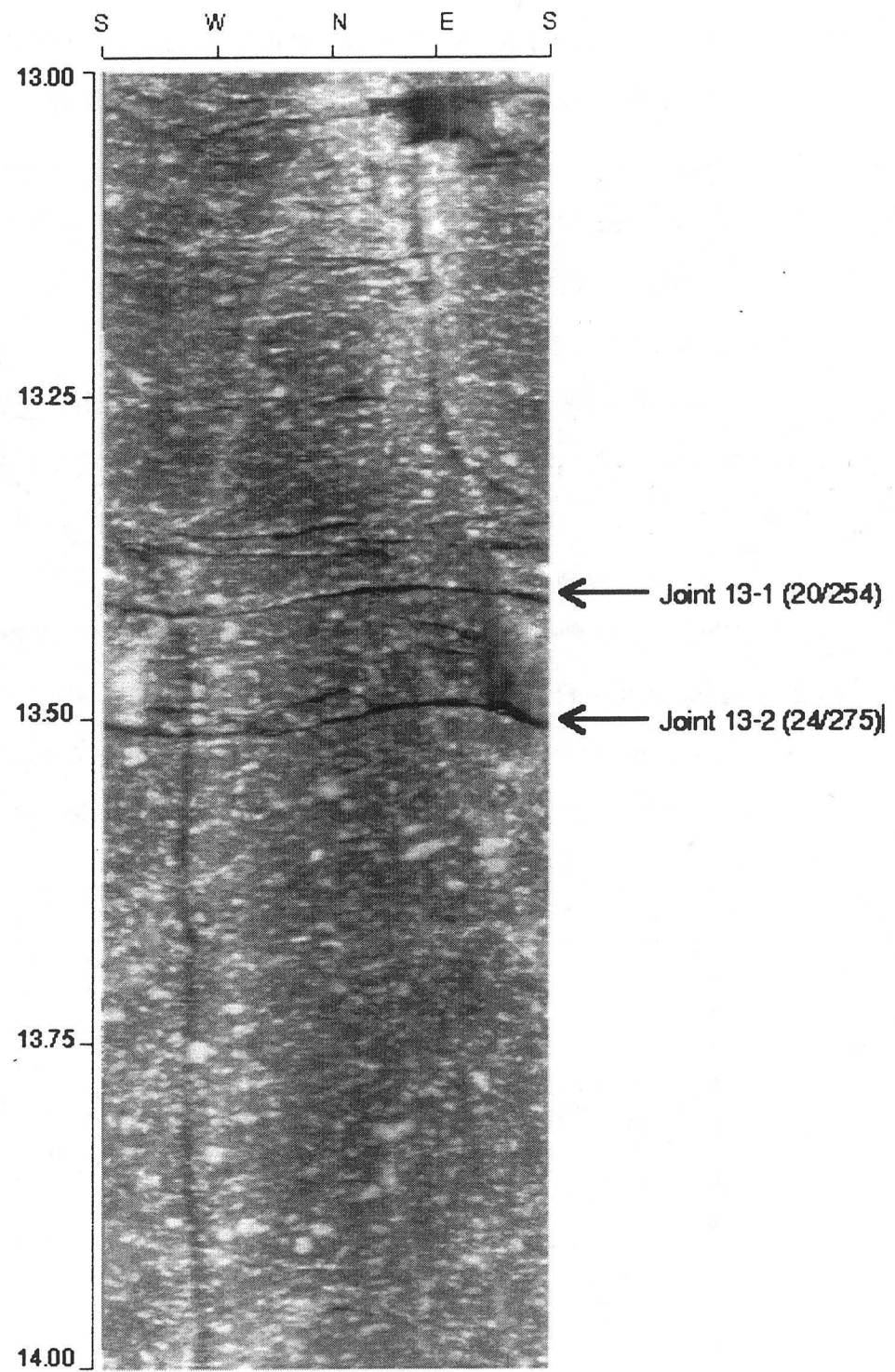


Figure 3.6: Original image showing joint 13-1|

The threshold network flow diagram implemented in AVS is shown in Figure 3.5. The network first reads the BSS image file and displays it in a window. The user can magnify the displayed image to get a closer look at the joint. The 'image probe' module allows the user to see the intensity of any pixel selected by the mouse and thereby identify a region with a constant upper threshold limit. Next, the 'sketch roi' module allows the user to define a Region Of Interest (ROI) using the mouse. Once the ROI has been defined, Eqn. (3.1) is used as coded in the 'ip threshold' module to analyze that region, and a binary image,  $g(x,y)$ , of the ROI is saved on a disk file. The entire joint is covered by repeating this procedure in as many ROI's as needed.

### 3.3.2 Edge locator network

The edge locator network operates on the binary ROI produced by the threshold network. The binary ROI from the threshold network is directly fed to the edge locator network so that the ROI does not have to be redefined. Figure 3.7 shows the edge locator network.

The 'edge locator' module shown in Figure 3.7 is not an AVS module. The code written for 'edge locator' scans through the ROI and applies the rules described earlier for isolating roughness profile pixels. The resulting roughness profile is exactly one pixel thick. The 'sketch roi' and associated modules in the edge locator network are used only if the ROI has to be redefined. The result of applying the edge locator network to joint 13-1 is shown in Figure 3.8. The roughness profile pixels in Figure 3.8 have been overlain on the original BSS image.

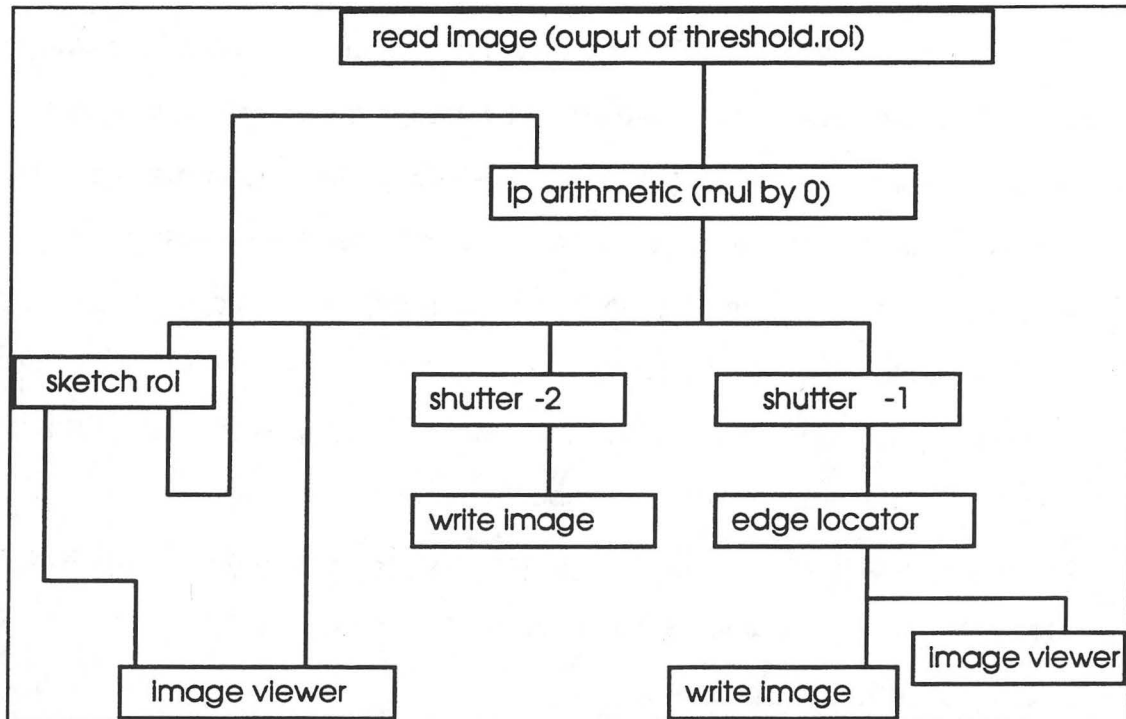
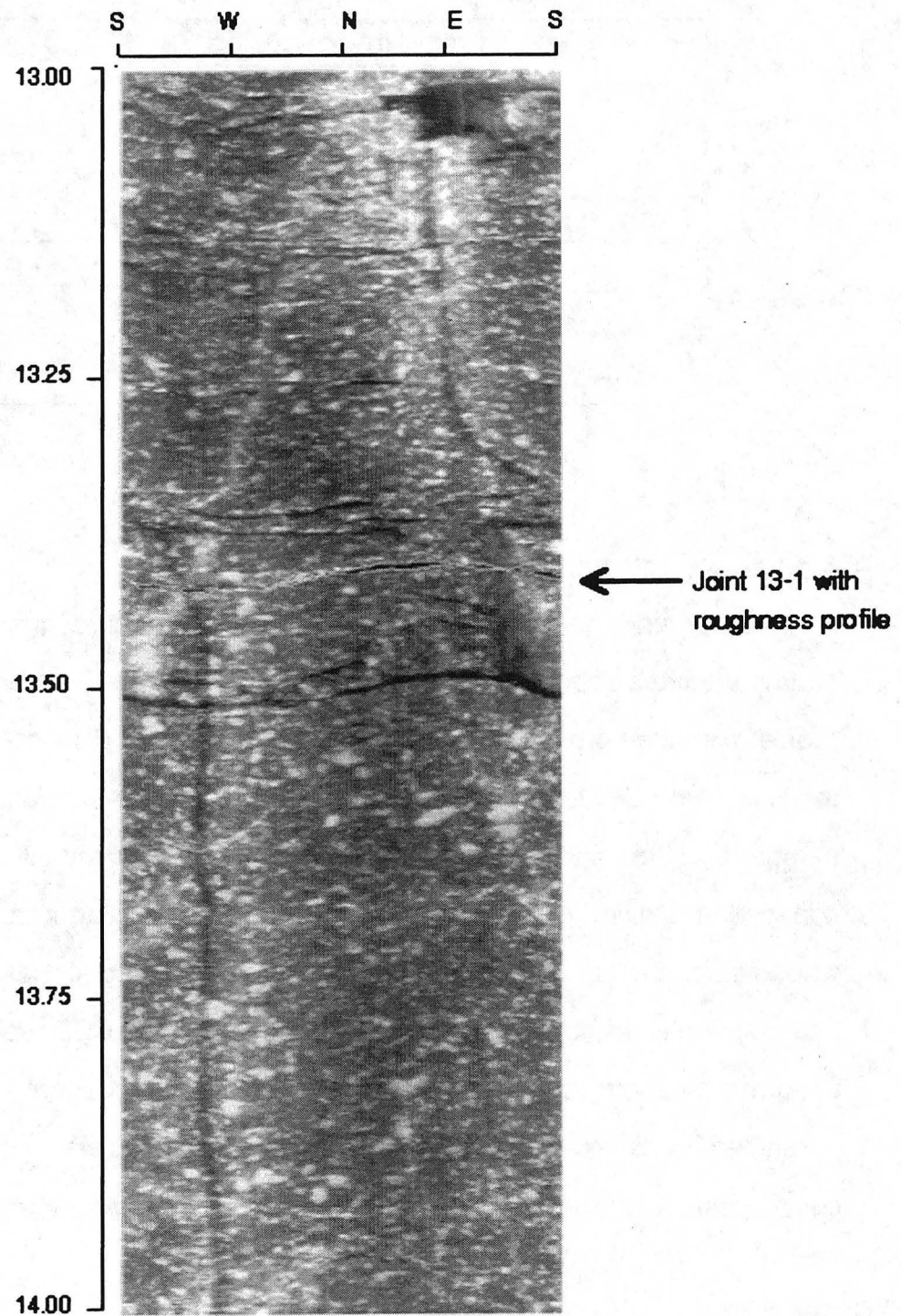


Figure 3.7: Edge locator network

### 3.3.3 Profiler network

The 'get profile' module of the profiler network was written to implement the pixel connectivity search pattern shown in Figure 3.4. The user defines the coordinates of the first pixel on either the upper or lower profile. Those coordinates can be found by using the 'image probe' module. The upper and lower profiles are processed independently and the user must specify which profile is being analyzed. Figure 3.9 shows the profiler network. Table 3.1 shows a partial listing of the image coordinates of profile points for joint 13-1. The full list contains 550 points and is listed in Appendix A.



**Figure 3.8: Overlay of joint 13-1 roughness profile on unrolled image of borehole wall**

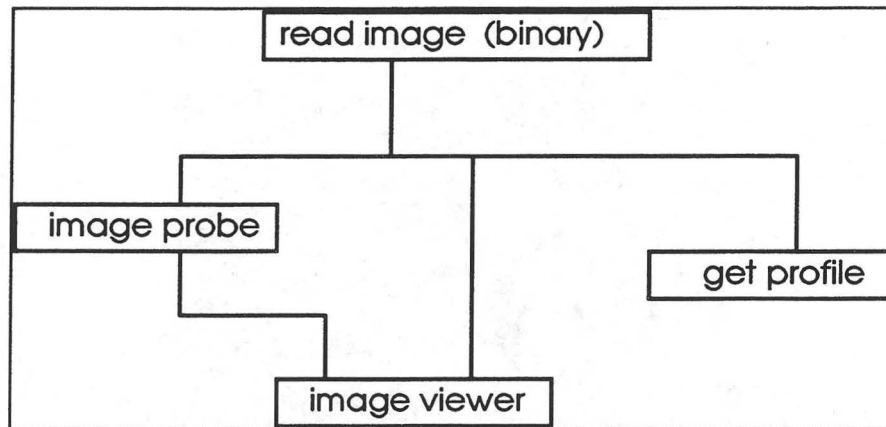


Figure 3.9: Profiler network

#### 3.3.4 Coordinate transforms

AVS is not needed once the ASCII file containing roughness profile image coordinates has been obtained from the profiler network. The last step in the profile extraction procedure is the coordinate transform discussed earlier. Once the image coordinates have been converted to borehole coordinates of rotation number and depth, the rotation number is further converted into an azimuth. The conversion to azimuth is done by linear interpolation between rotation numbers whose azimuths are known from the BSS data recording format. The linear interpolation is justified because the rotation rate of the BSS probe's mirror is uniform as it scans each line of the borehole wall. The roughness profile pixel borehole coordinates are partially listed in Table 3.1. As with the image coordinates, a full listing is given in Appendix A.



Table 3.1: Partial list of roughness profile for joint 13-1

| Upper profile of joint 13-1 |            |             |            | Lower profile of joint 13-1 |            |             |            |
|-----------------------------|------------|-------------|------------|-----------------------------|------------|-------------|------------|
| rotation                    | depth data | azimuth     | depth data | rotation                    | depth data | azimuth     | depth data |
| data                        | in image y | by global_c | in mm      | data                        | in image y | by global_c | in mm      |
| 1                           | 650        | 180.72      | 13428.25   | 1                           | 655        | 180.72      | 13434.5    |
| 2                           | 650        | 181.44      | 13428.25   | 2                           | 655        | 181.44      | 13434.5    |
| 3                           | 650        | 182.16      | 13428.25   | 3                           | 656        | 182.16      | 13432.25   |
| 4                           | 650        | 182.88001   | 13428.25   | 4                           | 656        | 182.88001   | 13432.25   |
| 4                           | 651        | 182.88001   | 13430.25   | 4                           | 655        | 182.88001   | 13434.5    |
| 5                           | 651        | 183.60001   | 13430.25   | 5                           | 655        | 183.60001   | 13434.5    |
| 6                           | 651        | 184.32001   | 13430.25   | 6                           | 655        | 184.32001   | 13434.5    |
| 7                           | 651        | 185.03999   | 13430.25   | 7                           | 655        | 185.03999   | 13434.5    |
| 7                           | 652        | 185.03999   | 13430.75   | 8                           | 655        | 185.76      | 13434.5    |
| 8                           | 652        | 185.76      | 13430.75   | 9                           | 655        | 186.48      | 13434.5    |
| 8                           | 653        | 185.76      | 13433      | 10                          | 655        | 187.2       | 13434.5    |
| 9                           | 653        | 186.48      | 13433      | 11                          | 656        | 187.92      | 13432.25   |
| 10                          | 653        | 187.2       | 13433      | 12                          | 656        | 188.64      | 13432.25   |
| 11                          | 653        | 187.92      | 13433      | 13                          | 657        | 189.36      | 13434.5    |
| 11                          | 654        | 187.92      | 13432.25   | 14                          | 657        | 190.08      | 13434.5    |
| 12                          | 654        | 188.64      | 13432.25   | 15                          | 657        | 190.8       | 13434.5    |
| 13                          | 654        | 189.36      | 13432.25   | 16                          | 658        | 191.52      | 13433.5    |
| 13                          | 655        | 189.36      | 13434.5    | 17                          | 659        | 192.24001   | 13434      |
| 14                          | 655        | 190.08      | 13434.5    | 18                          | 660        | 192.96001   | 13436      |
| 14                          | 656        | 190.08      | 13432.25   | 18                          | 661        | 192.96001   | 13436.75   |
| 15                          | 656        | 190.8       | 13432.25   | 19                          | 662        | 193.67999   | 13436      |
| 16                          | 656        | 191.52      | 13432.25   | 20                          | 663        | 194.39999   | 13435.25   |
| 17                          | 656        | 192.24001   | 13432.25   | 21                          | 664        | 195.12      | 13435.75   |
| 17                          | 657        | 192.24001   | 13434.5    | 22                          | 664        | 195.84      | 13435.75   |
| 18                          | 657        | 192.96001   | 13434.5    | 23                          | 664        | 196.56      | 13435.75   |
| 19                          | 657        | 193.67999   | 13434.5    | 24                          | 664        | 197.28      | 13435.75   |
| 20                          | 657        | 194.39999   | 13434.5    | 25                          | 664        | 198         | 13435.75   |

## **CHAPTER 4**

### **ANALYSIS FOR IN-SITU MECHANICAL JOINT PROPERTIES**

#### **4.1 Overview**

In-situ joint profiles obtained from BSS images may be analyzed for a number of mechanical joint properties. Analyses developed for estimating in-situ joint dilation angles and shear strength are described in this chapter.

Considerations related to joint aperture estimation that grew out of the work on mechanical properties are also described.

The BSS data used in developing and testing the methods described in this thesis were collected from two vertical boreholes 3-5 and 4-1 at a site of a proposed underground powerhouse in the central part of Honshu Island in Japan. The two boreholes are located in an exploratory adit situated 70 meters beneath a steep valley where the basement rocks are porphyritic granite, rhyolite and slate. The site was subjected to late Cretaceous volcanic movement and contains many steeply dipping joints with high joint frequency and wide apertures (Tanimoto et. al, 1994).

A total of 30 joints from borehole 3-5 and 2 joints from borehole 4-1 were used in this thesis. Unrolled images of the parts of boreholes 3-5 and 4-1 containing these joints are presented in Appendix B. The joints will be referred to by the identification labels shown in the images of Appendix B. Unfortunately, the scanning rate used at the site was not optimal and as a result the vertical resolution of the BSS data is only 0.5 mm. The scanner version used at the time of the scanning had a maximum vertical resolution of 0.25 mm. The horizontal resolution of the data is 0.56 mm. This too could have been improved to 0.25 mm had the 1000 pixel format data been available. All joints from borehole 3-5 were in porphyritic granite and all joints in borehole 4-1 were in rhyolite.



Opposing roughness profiles were extracted from all joints using the method discussed in Chapter 3.

## 4.2 Joint Dilatancy and Renger's envelope

Following a review of the role of joint roughness in shear strength, a method of analyzing the BSS data for the joint dilation angle is presented in this section.

### 4.2.1 Background

The peak shear strength of joints,  $\tau$ , is a stress dependent property that is controlled by joint surface friction and dilation. Additionally, the shear strength may be influenced by rotation and rolling effects on the joint surface, cementation (Goodman, 1976) and rock bridges. Patton (1966) expressed joint shear strength by

$$\begin{aligned}\tau &= \sigma \tan(\phi_{\mu} + i) && \text{for low } \sigma \\ \tau &= S_j + \sigma \tan \phi_r && \text{for high } \sigma\end{aligned}\quad (4.1)$$

where  $\sigma$  is the normal stress acting across the joint,  $\phi_{\mu}$  is the basic friction angle,  $i$  is the joint dilation or roughness angle,  $S_j$  is the shear strength intercept and  $\phi_r$  is the residual friction angle. Figure 4.1 illustrates this bilinear shear strength criterion.

The expression for  $\tau$  in low normal stress conditions, known as Patton's law, accounts for the shear resistance caused by overriding of asperities inclined at  $i$  degrees to the mean joint plane during the shearing process. Figure 4.2 illustrates the limit equilibrium condition that gives rise to the additional shearing resistance caused by inclined asperities. In addition to the peak shear strength, the shape of the shear stress - shear deformation curve and the rate of dilatancy are also controlled by surface roughness (Goodman, 1989).

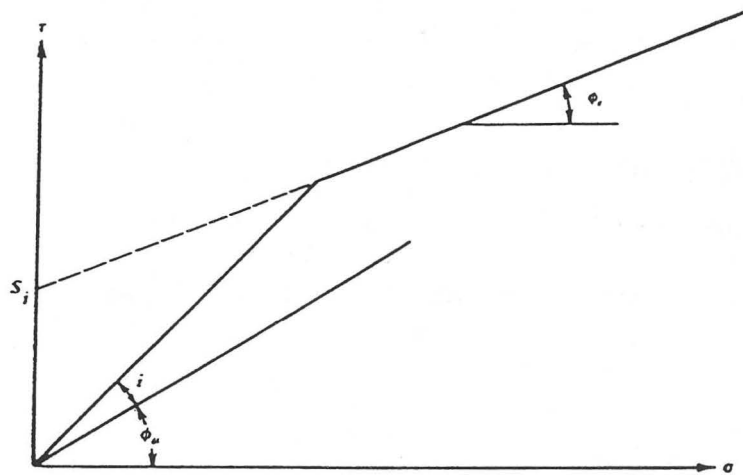


Figure 4.1: Bilinear shear strength criterion (after Goodman, 1976)

With increasing normal stress, less shearing force is required to shear through the asperities than to override them. Under such conditions, Patton's law is replaced by an expression that combines the shear strength intercept and the residual friction angle as shown in Figure 4.1 and Eqn. (4.1). Goodman (1976) provides a review of alternate equations to the bilinear criterion.

In addition to its contribution to shear strength through the dilation angle, surface roughness also brings about an increase in shear strength in confined conditions due to the volume change it causes. If the blocks on either side of the joint are not free to dilate as shear displacement takes place, additional normal stress is developed across the joint. This increase in normal stress increases the shearing resistance over the next increment of shear displacement. Heuze (1979) gives analytical expressions for increments of normal stress developed under such circumstances and Boyle (1980) shows the influence of this phenomena on block stability using a block reaction curve.

The fundamental role of joint surface roughness in shear strength has led to the development of several methods of measuring roughness profiles and dilation angles from accessible joint surfaces. Fecker and Rengers (1971)

measured dilation angles at various scales by measuring the orientation of flat plates of different lengths. Wire gauges profilometers have been used by Barton and Choubey (1977) for profiling along a line. Similarly, profiles have been obtained using a laser sensor (Tanimoto et. al.) and from photographs using photogrammetric techniques (Miller et. al., 1989).

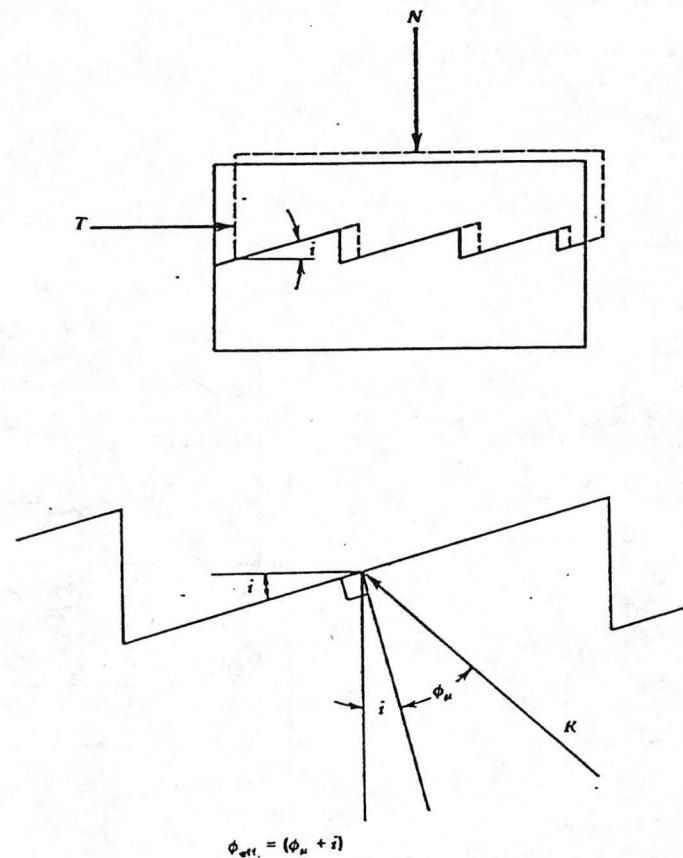


Figure 4.2: Limit equilibrium represented by Patton's law (after Goodman, 1989)

Analysis of joint roughness profiles for the dilation angle is done by making repeated measurements of lines connecting profile points separated by a range of base lengths, as first described by Rengers (1970). The roughness angles measured in this way are plotted as a function of base length. The

envelope to all points plotted in this way is known as the Rengers envelope. Figure 4.3 illustrates Rengers method and the resulting envelope. The roughness angle for the displacement distance of interest can be read off directly from the Rengers envelope and used in Eqn. (4.1) to estimate the joint shear strength. Barton and Choubey (1977) recommend using 1% of the block size as the peak displacement distance. In addition to the shear strength, Rengers envelope can also be used for calculating the dilatancy and shear deformation curves, as described by Schneider (1976).

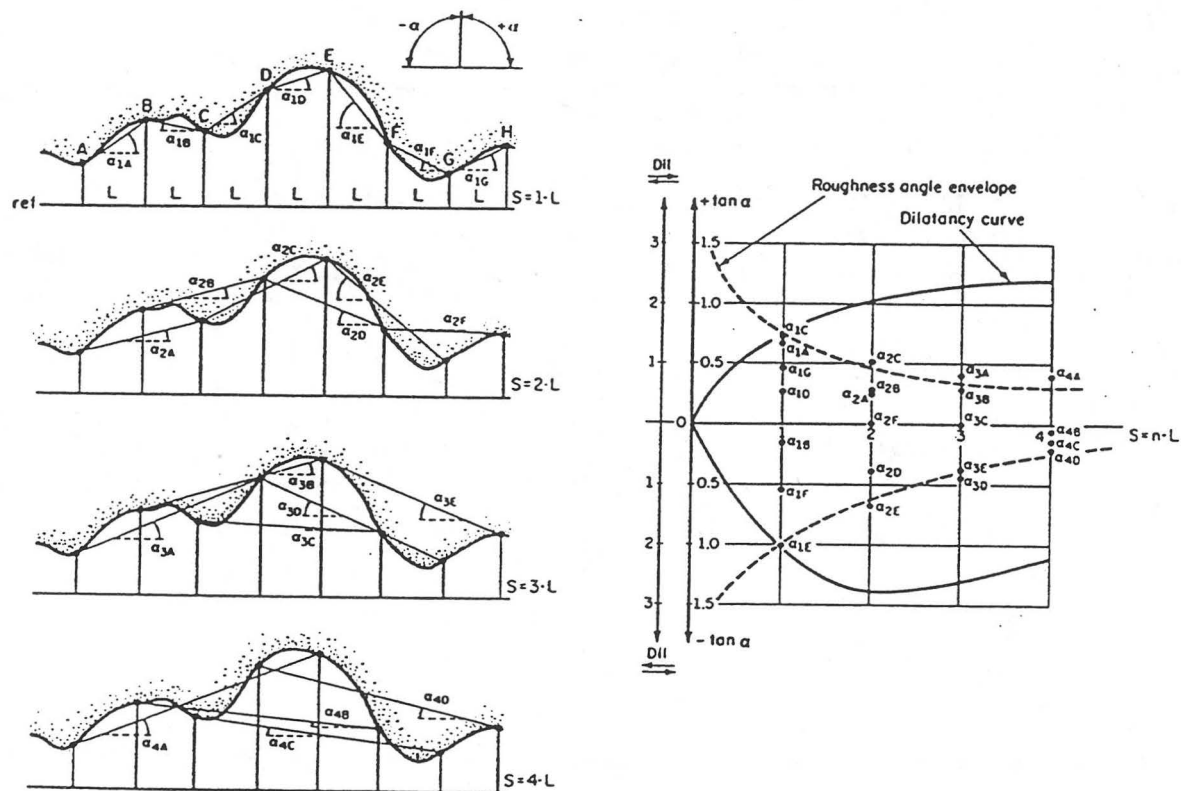


Figure 4.3: Rengers roughness analysis and envelope (after Goodman, 1976)

#### 4.2.2 Estimation of Rengers envelopes using BSS profiles

The roughness profile points extracted from the BSS image constitute a sample of the joint surface topography along a path determined by the intersection of the borehole with the joint surface. This interpretation of the BSS

profile is based on an assumption that the drilling process has not altered the joint roughness. Furthermore, the borehole is assumed to be circular and vertical for the calculation of the location of all image pixels. The difference between the BSS derived sample and profiles obtained by other methods is the non-linear profiling path and in-situ measurement in the case of the BSS profile.

As described earlier, calculation of the dilation angle is done with respect to a mean joint plane. The shearing process is assumed to involve translation along this mean translation plane and dilation normal to it but no rotation about it. One way to determine the orientation the mean translation plane is to use the estimate of the orientation of the joint in the BSS image. This method has the disadvantage of misrepresenting the mean translation plane due to local joint waviness. An alternate method is to fit planes between sets of three contacting points on the joint and use the mean of these planes as the mean translation plane. However, this method cannot be used on joints where there are no contacting points in the BSS sample of the opposing joint surfaces. The joint orientation measured in the BSS image is assumed to be the mean translation plane in this thesis. The Expert program was used to estimate the joint orientations.

The roughness angle is calculated from the angle between chords connecting profile points and the normal vector to the mean translation plane:

$$i = 90 - \tan^{-1} \left( \frac{\bar{c} \cdot \bar{n}}{\|\bar{n}\|} \right) \quad (4.2)$$

where  $\bar{c}$  is the chord vector connecting two profile points and  $\bar{n}$  is the joint unit normal vector. The unit joint normal vector  $n(a,b,c)$  is obtained from the strike ( $\alpha$ ) and dip ( $\beta$ ) of the joint as

$$\begin{aligned}
 a &= \sin \alpha \sin \beta \\
 b &= \sin \alpha \cos \beta \\
 c &= \cos \alpha
 \end{aligned}
 \tag{4.3}$$

The magnitude of the base length,  $d$ , for each chord is

$$d = \|c\| \cos(i) \tag{4.4}$$

Rengers envelope for a specific sliding direction can be constructed by finding the maximum roughness angles made by all chords pointing in the sliding direction. The upper and lower joint profiles are evaluated individually. For each  $(i, d)$  pair of the envelope calculated for a certain sliding direction, there will be a symmetric  $(-i, d)$  pair for the opposite direction. The upper limit of the base length that can be obtained depends on the borehole size and the dip angle of the joint. In the case of joints analyzed in boreholes 3-5 and 4-1, this upper limit is about 90 mm. The lower limit of the base length depends on the resolution.

If the surface roughness of the joint being analyzed is isotropic, the construction of the Rengers envelope can utilize all pairs of profile points for calculating  $(i, d)$  pairs, and not just those that define chords in a specific direction. The increase in the number of profile sample point pairs used in this case leads to a more reliable Rengers envelope. Evaluation of joint isotropy is described later in this chapter.

A computer program was written to implement the method described above. The program reads in points on a profile, calculates pairs of  $(i, d)$  points in one or all directions and prints the results to an ASCII file. In order to verify the program, it was tested using a synthetic profile generated from points of intersection of a vertical borehole and a smooth joint plane. The Rengers envelope produced by using the synthetic profile shows the roughness angle to be zero at all base lengths, as expected. At very small base lengths, the



roughness angle is greater than zero due to numerical errors as shown in Appendix C.

#### 4.2.3 Renger's envelopes for borehole 3-5 joints

Rengers envelopes were calculated for joints in borehole 3-5. Figure 4.4 shows Rengers envelopes for the upper and lower profiles of joint 19-1, which happens to be a joint with isotropic roughness as explained later. In the case of joint 19-1, the upper and lower profiles have nearly the same Rengers envelopes although the lower profile has consistently lower roughness angles at all scales by a few degrees. Unlike the perfectly mated opposing joint profiles analyzed by Rengers, the opposing profiles from BSS images will not necessarily produce identical envelopes. This is because the in-situ condition may not be one where the opposing profiles are perfectly mated. Infact, differences in the envelopes of opposing profiles may provide an indication of preferential joint wall alteration or wear of wall asperities. For instance, the slightly lower roughness angles of the lower profile in Figure 4.4 may be due to mineralogical alteration of the lower joint wall by unsaturated fluid flow.

The shape of the roughness angle curve shows a decreasing roughness angle with increasing displacement distance as expected. The roughness angle is seen to increase rapidly at displacement distances of less than 20 mm and decreases gradually at larger displacements. The large roughness angles observed at very small scales shown in Figure 4.4 is in agreement with similar conclusions reached by Barton (1980).

Rengers envelopes for joint 21-1, which has anisotropic roughness, are shown in Figure 4.5 for the minimum and maximum roughness directions of each profile. As with joint 19-1, joint 21-1 has similar envelopes on opposing profiles. However, the anisotropy of joint 21-1's surface roughness results in a substantial difference in the envelopes taken in the maximum and minimum

roughness directions (analysis for the maximum and minimum roughness directions are described later). The difference in roughness angle is lowest at small displacement distances and increases to a high value of about 20 degrees at a displacement distance of about 45 mm. Thereafter, the difference decreases gradually.

Rengers envelopes for some additional joints from borehole 3-5 are given in Appendix D.

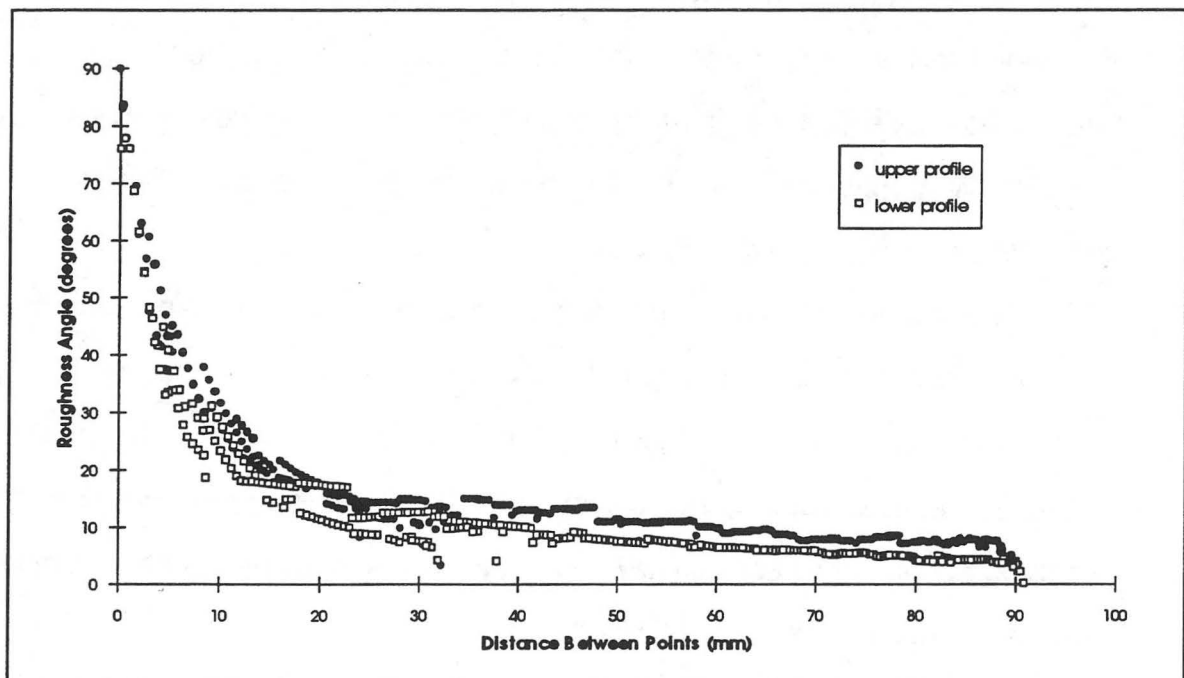


Figure 4.4: Rengers envelopes for opposing profiles of joint 19-1



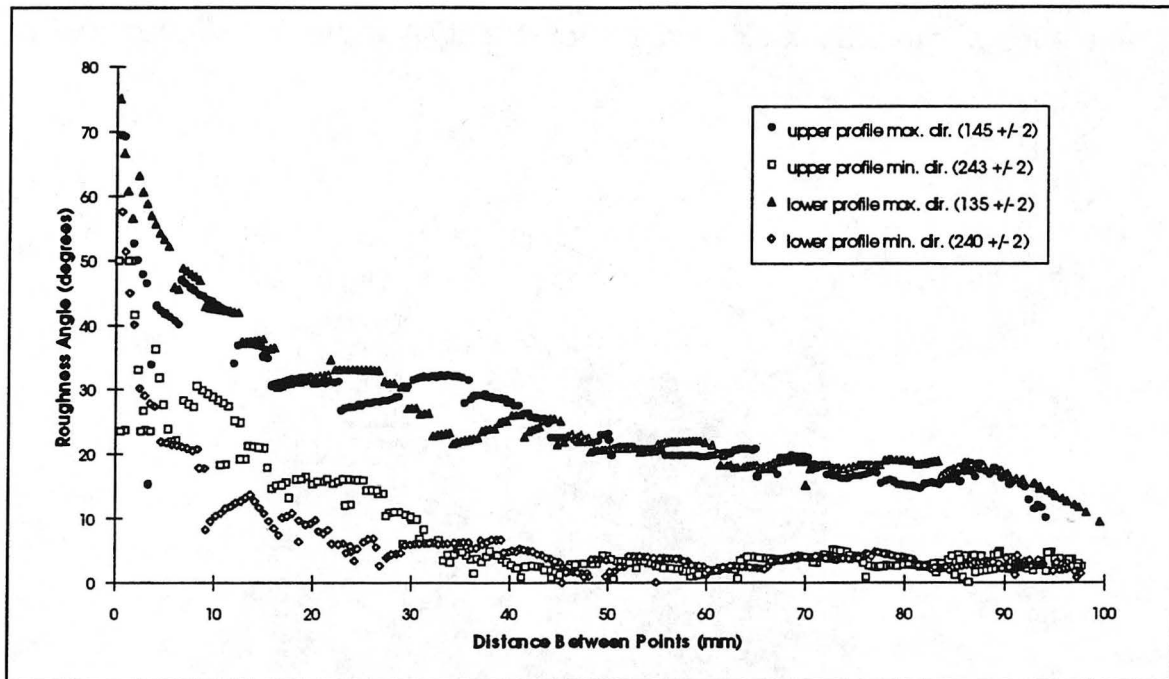


Figure 4.5: Rengers envelopes for opposing profiles of joint 21-1

### 4.3 Dilation angle anisotropy

After a brief review of the sources, importance and existing analysis of surface roughness, this section describes how dilation angle anisotropy may be measured using BSS data. The method is then applied to joints from borehole 3-5.

#### 4.3.1 Background

The surfaces of natural joints may have some structure that leads to anisotropic roughness. Figure 4.6 shows a schematic drawing of some surface morphology features of joints described by Suppe (1985). The fringe is composed of a series of en-echelon fractures at the edge of the joint surface. Plumose structure consists of undulations along lines fanning out from a single point and terminating at the fringes. Conchoidal structures are discrete jumps in joint orientation occurring perpendicularly to the plumose structure lines. Other types of surface structures such as striations and ripple marks may also be observed. Figure 4.7 shows a saw-tooth surface structure from a joint in slate at

the Auburn dam site in California. All of these surface structures would lead to anisotropic dilation angles.

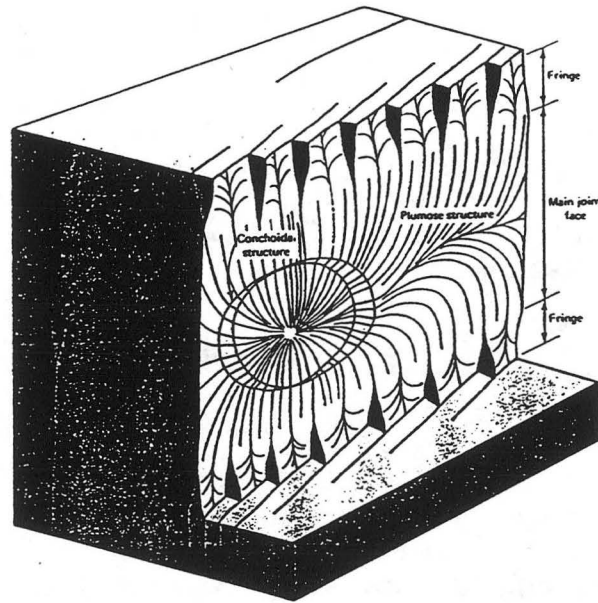


Figure 4.6: Schematic of joint surface morphology (after Suppe, 1985)

Dilation angle anisotropy leads to anisotropic joint strength. This fact makes dilation angle anisotropy a critical element in the stability of discontinuous rockmasses. Blocks defined by intersecting discontinuities are kinematically constrained to move only in certain directions. As a result of the dilation angle anisotropy, the directions in which key blocks may move could be relatively weak or strong depending on the joint strength.

Despite the importance of anisotropic dilation angles in deformation problems, the topic has received little attention in the past. Goodman (1976) presents an example of anisotropic roughness using a scatter plot of joint normals on a stereonet, and shows how the profiling direction leads to dilation angle anisotropy on a joint surface composed of planes with the same dip and



Figure 4.7: Saw-tooth joint morphology from Auburn dam, California

opposite dip directions. Huang and Doong (1990) performed laboratory direct shear tests on joint replicas in different directions and compared the results to predictions using Barton's equation (Barton and Choubey, 1977) based on profiles measured in nine separate directions. They found that the laboratory shear strengths were anisotropic, but that the anisotropy decreased with increasing normal stress. Also, they found that the analytical predictions using the anisotropic roughness profiles gave results which were close to the laboratory test results. Harrison and Goodfellow (1993) describe an analytical method of quantitatively evaluating roughness anisotropy at various scales using

multivariate statistics. After applying the method on four joints, they found that the roughness anisotropy decreases with increasing scale.

#### 4.3.2 Method of anisotropy analysis - example of joint 10-1

The analysis of the BSS derived roughness profiles for dilation angle anisotropy is the same as the analysis for the roughness angle in terms of calculating pairs,  $(i, d)$ , of dilation angles and baselengths. However, in the case of the anisotropy analysis, the azimuth of the vector connecting pairs of profile points is also calculated, so that the result consists of a list of triplets  $(i, d, a)$  where  $a$  stands for the azimuth of the vector defining the triplet. Note that these triplets correspond to the maximum dilation angle in a given direction and at a certain scale.

The anisotropy analysis method was coded in a program. The program reads pairs of points defining one joint profile and prints out a file containing pairs of  $(i, a)$  points at up to five scale intervals chosen by the user. The program was tested on the already mentioned synthetic profile data. The first test case was a smooth joint (45/180) which gave a computed dilation angle of zero in all directions at all scales. In a second test, the synthetic profile for a smooth flat joint was modified by raising the z axis position of profile points between azimuths 85 and 90, by 5 mm. As expected, at a scale slightly larger than the borehole diameter, the roughness angle was greater than zero between azimuths 85 and 90 while the roughness angle remained zero in other directions. The second test was repeated on a smooth plane inclined at 45 degrees and the program was found to give correct results for this test profile as well. The results of the first two verification tests are given in Appendix E.

The  $(i, a)$  data pairs generated by the anisotropy analysis program are used to produce an anisotropy curve for each opposing joint profile as shown in

Figure 4.8 for joint 10-1 in borehole 3-5. The anisotropy curve of Figure 4.8 is presented in terms of four scale intervals.

#### 4.3.3 Interpretation of anisotropy curves

Interpretation of the joint surface topography from the anisotropy curve of Figure 4.8 is an inverse problem. Different surface shapes will produce different anisotropy curves. Furthermore, as with any inverse problem, the solution to the surface topography problem may not be unique -- i.e. more than one surface topography model may satisfy the anisotropy curve. The simplest anisotropy curve would be a flat line within a small roughness angle interval. For this case, the joint surface model would simply consist of a smooth plane. The first and third tests used to verify aniso.c correspond to this case (see Appendix A.5). As the shape of the anisotropy curve becomes more complex, the interpretation also becomes more difficult. In this thesis trial and error is used to find a surface model that fits the anisotropy curve.

It is not always necessary to find a surface topography model to use the anisotropy curve. For mechanical stability problems for instance, just knowing whether there is any anisotropy will enable further analysis to account for the effect of surface shape. If the surface is found to be anisotropic, Rengers envelopes will have to be taken in the sliding direction only. Direct shear tests should also be done in the sliding direction in this case.

The deviation of joint surfaces from planarity is generally considered to be the result of roughness at small scales and waviness at large scales. Since undulations at both scales can affect the peak shear strength, it is necessary to determine the scale of interest before attempting to interpret anisotropy curves. For mechanical problems, Barton and Choubey's (1977) recommendation of using 1% of the joint length as the peak shear displacement distance can be

Fig. 4.8(a.1): Anisotropy curve for lower profile of joint 10-1 at a scale of 4.5 to 5.5 mm

dip=16 degrees, dip.dir=340 degrees

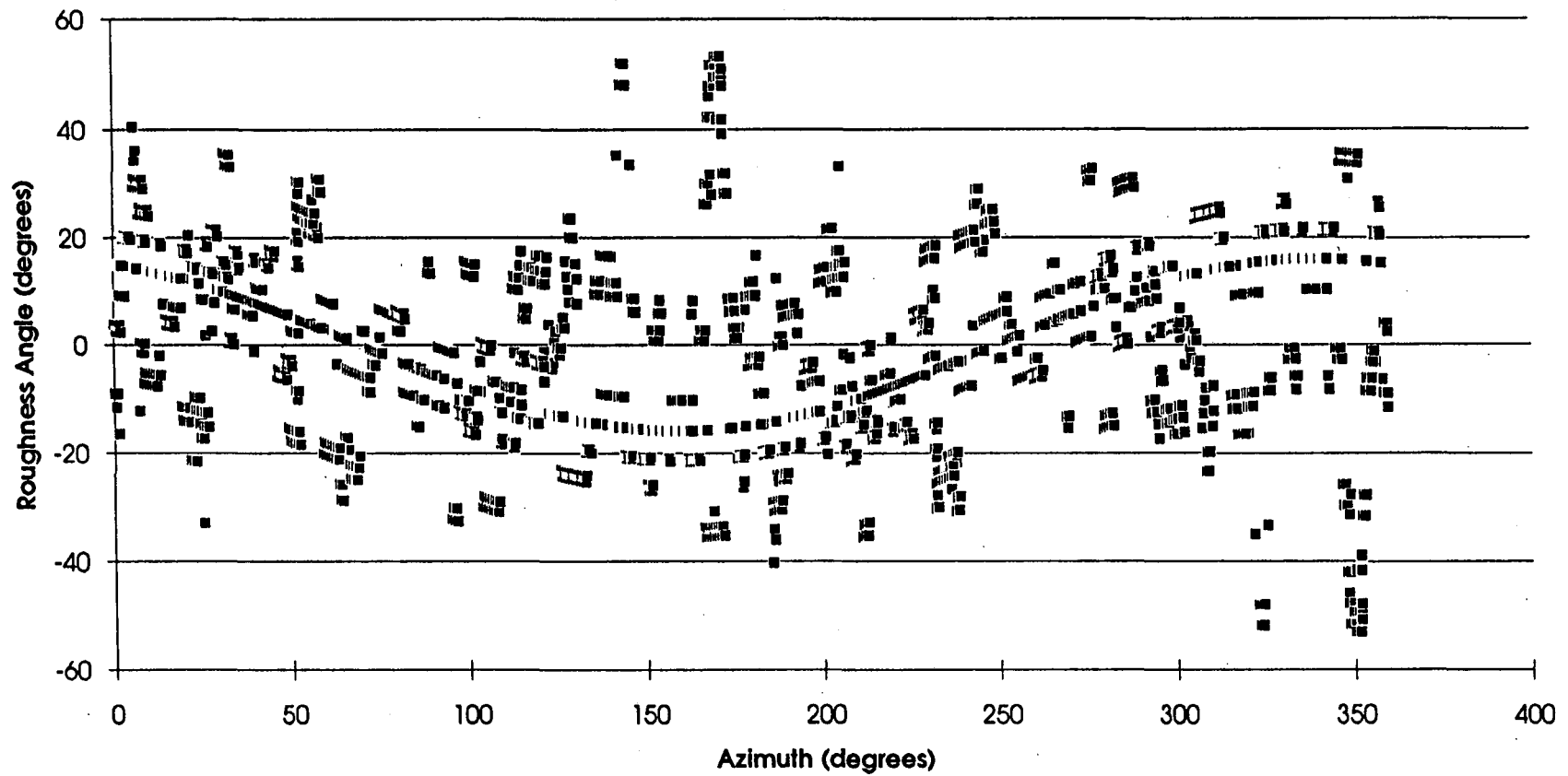
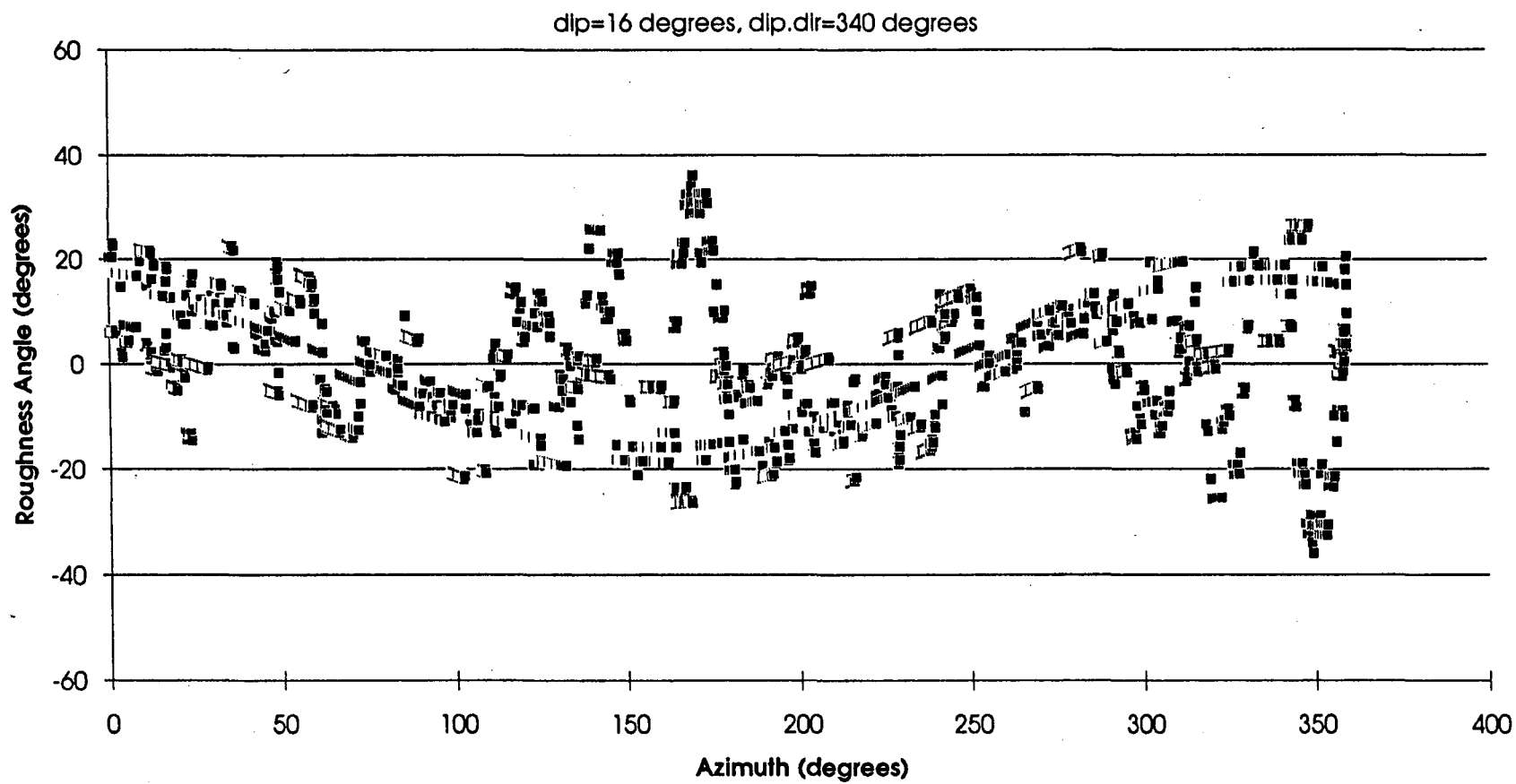
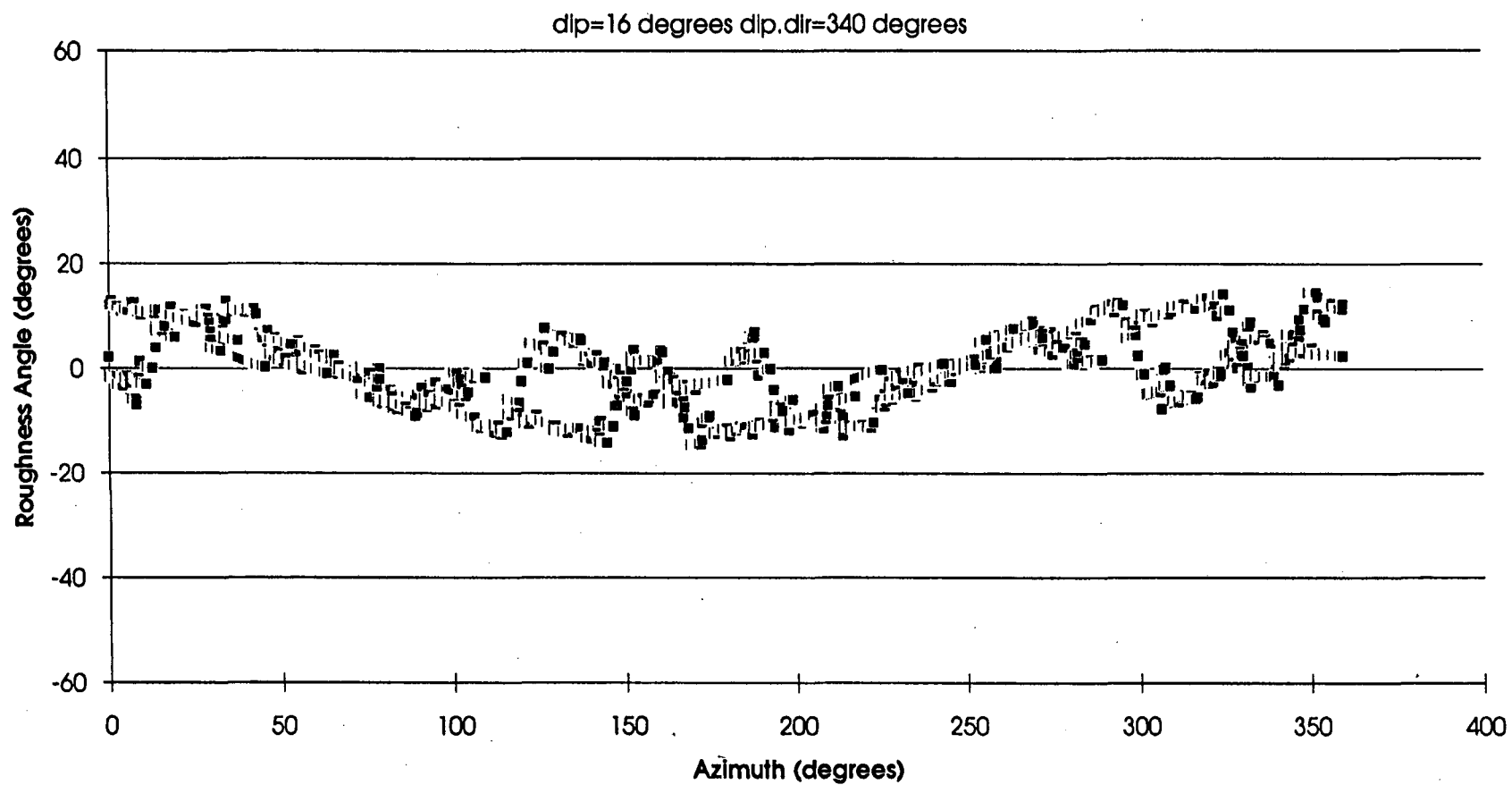


Fig. 4.8(a.2): Anisotropy curve for lower profile of joint 10-1 at a scale of 9.5 to 10.5 mm



**Fig.4.8(a.3): Anisotropy curve for lower profile of joint 10-1 at a scale of 34.5 to 35.5 mm**





**Fig. 4.8(a.4): Anisotropy curve for lower profile of joint 10-1 at a scale of 49.5 to 50.5 mm**

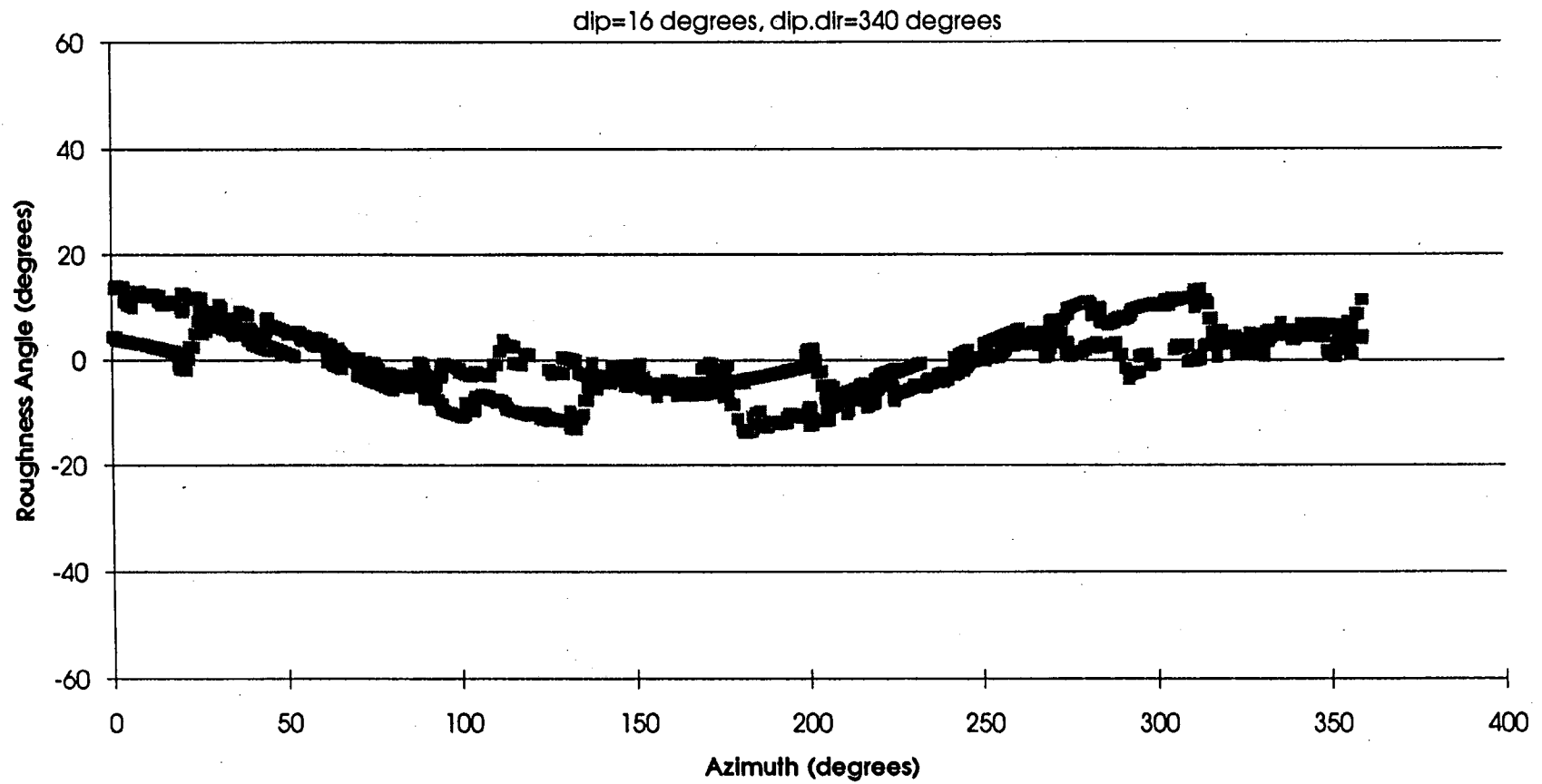


Fig. 4.8(b.1): Anisotropy curve for upper profile of joint 10-1 at a scale of 4.5 to 5.5 mm

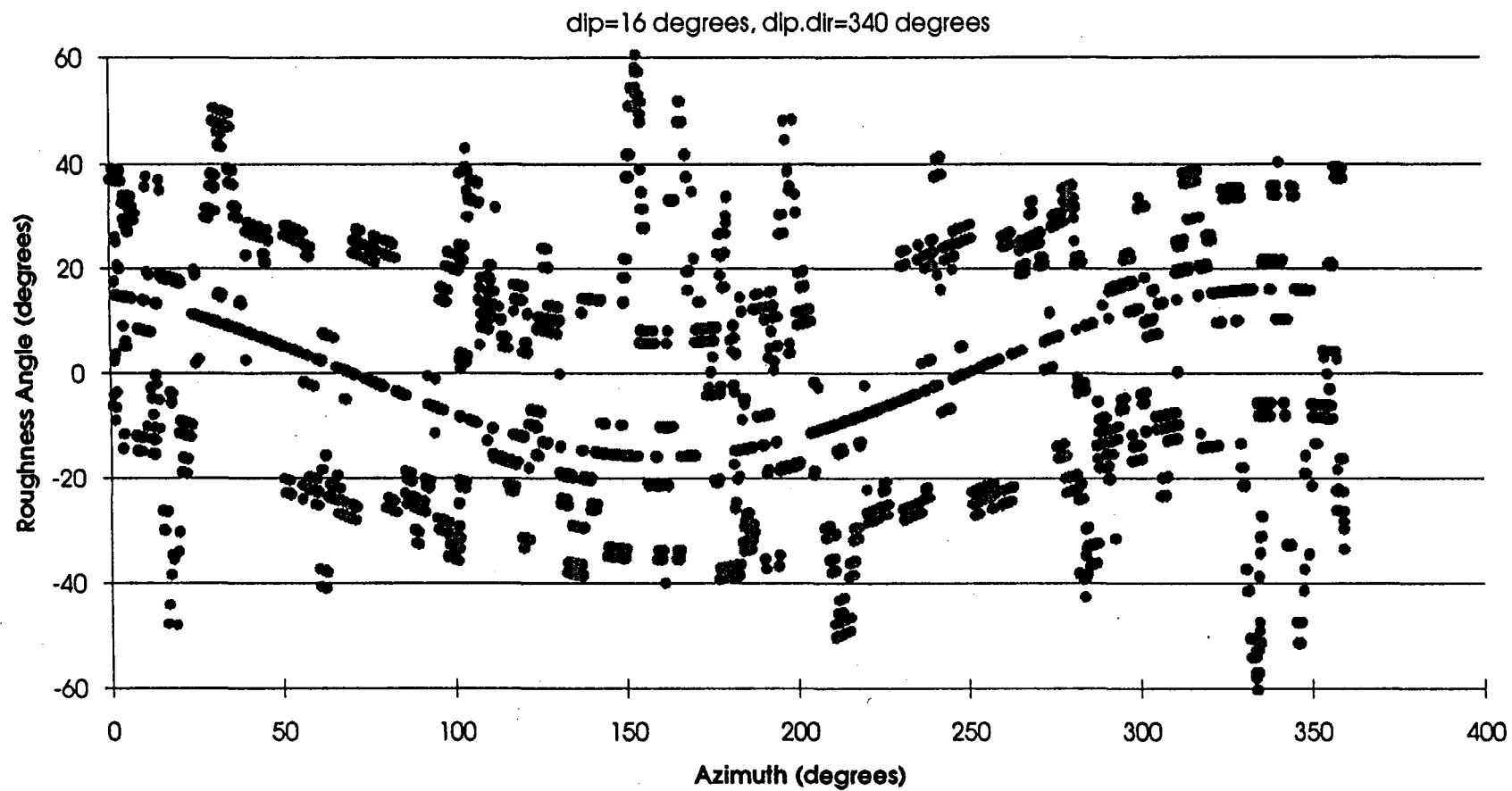
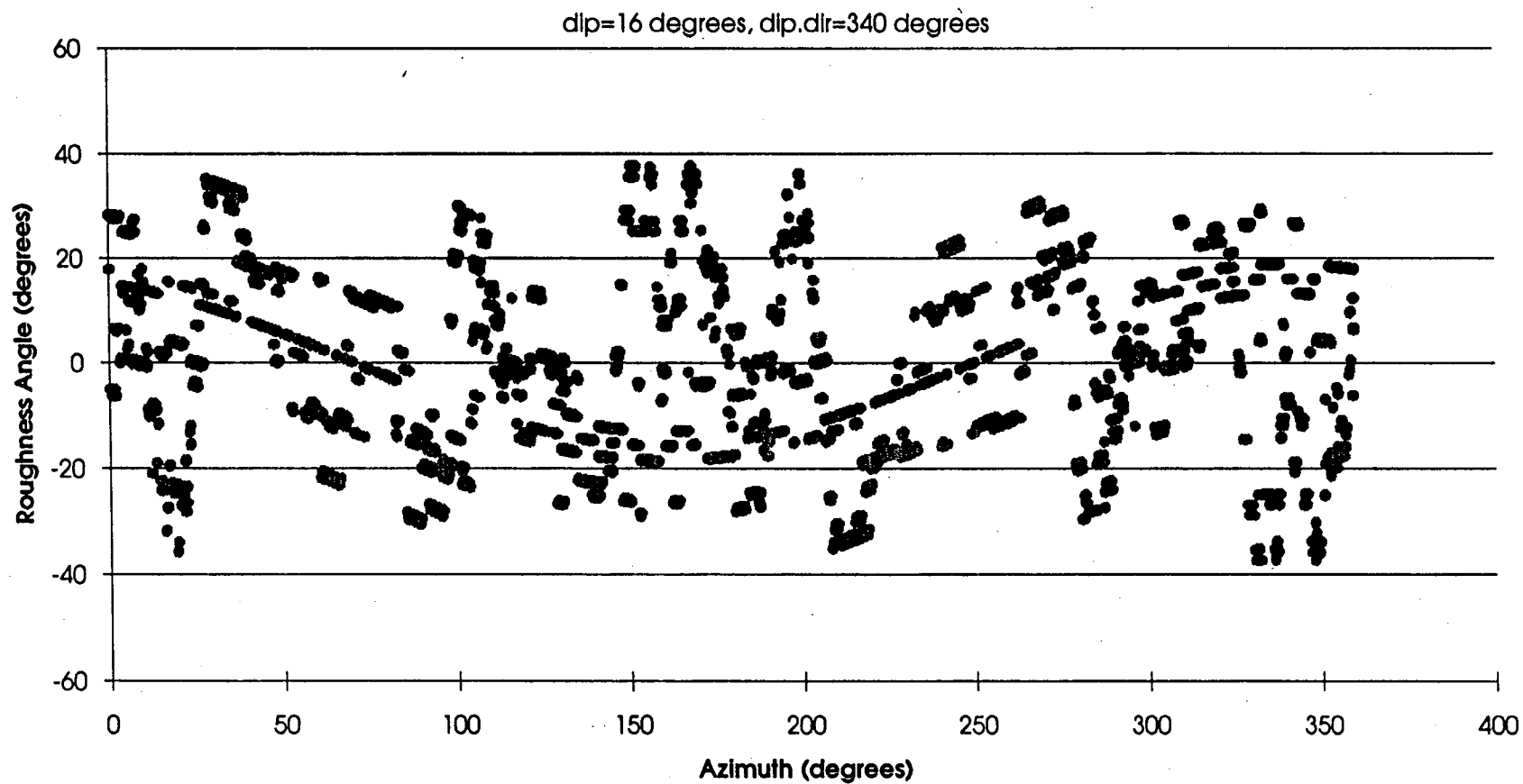
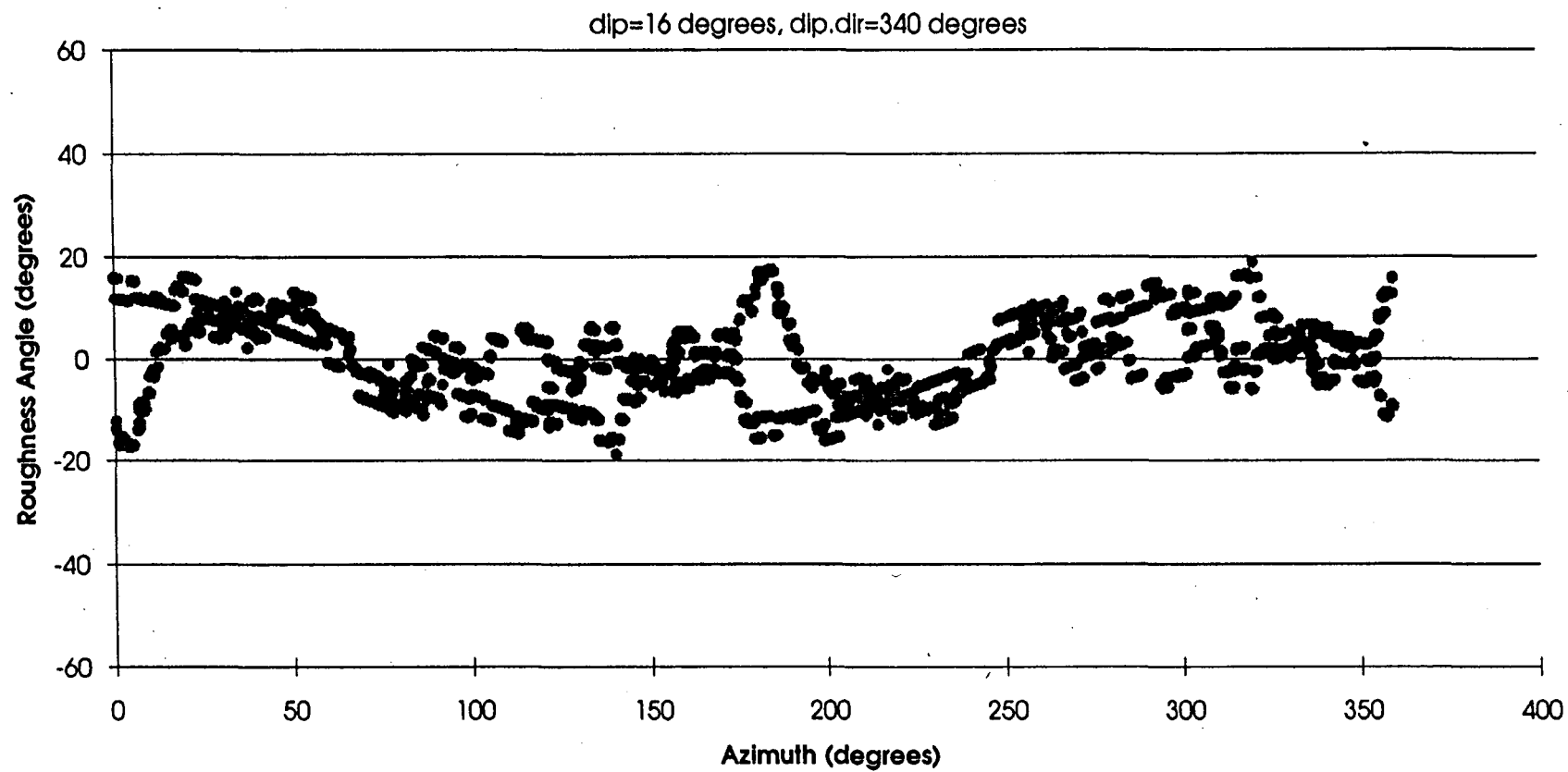


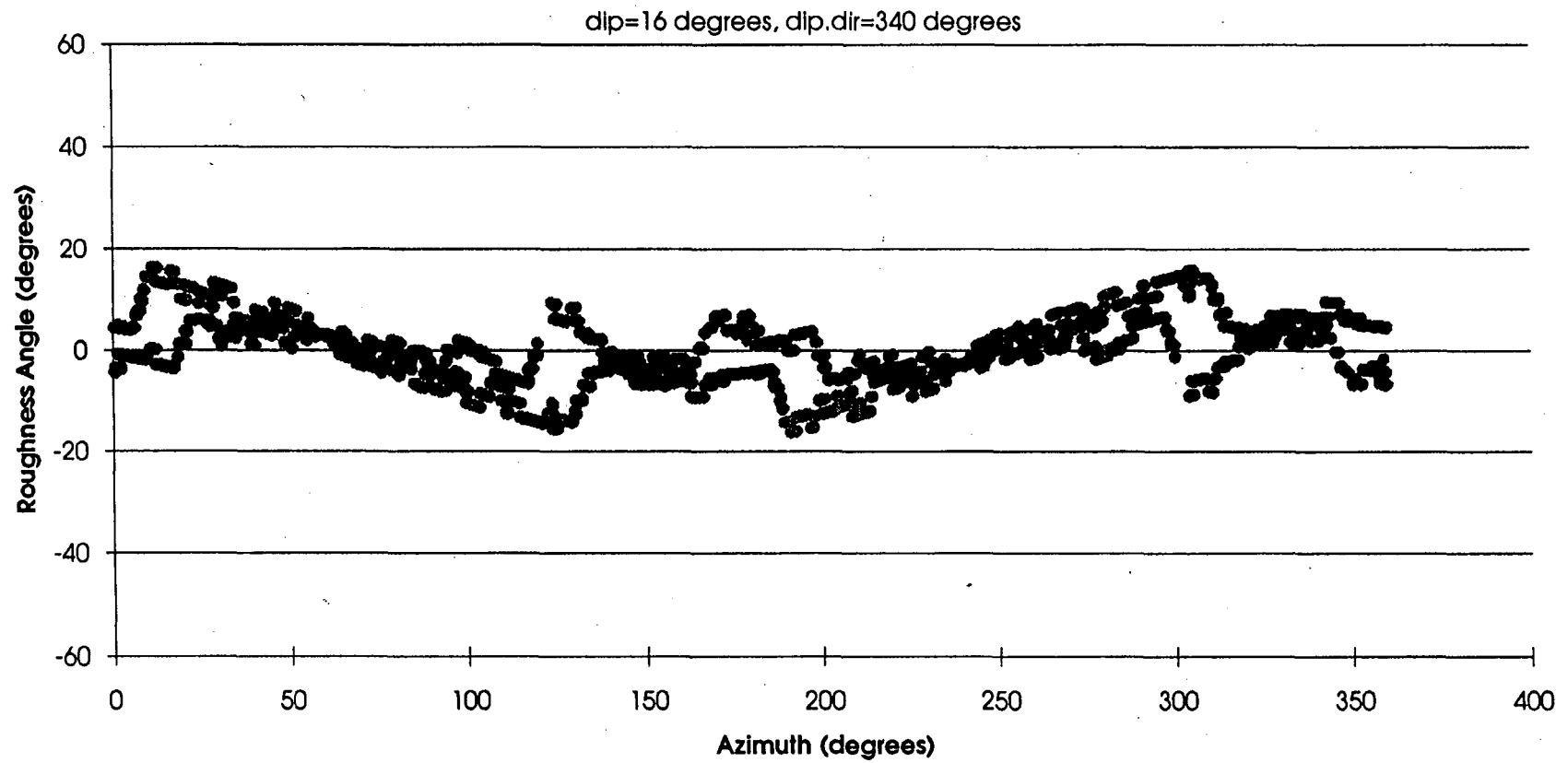
Fig. 4.8(b.2): Anisotropy curve for upper profile of joint 10-1 at a scale of 9.5 to 10.5 mm



**Fig. 4.8(b.3): Anisotropy curve for upper profile of joint 10-1 at a scale of 34.5 to 35.5 mm**

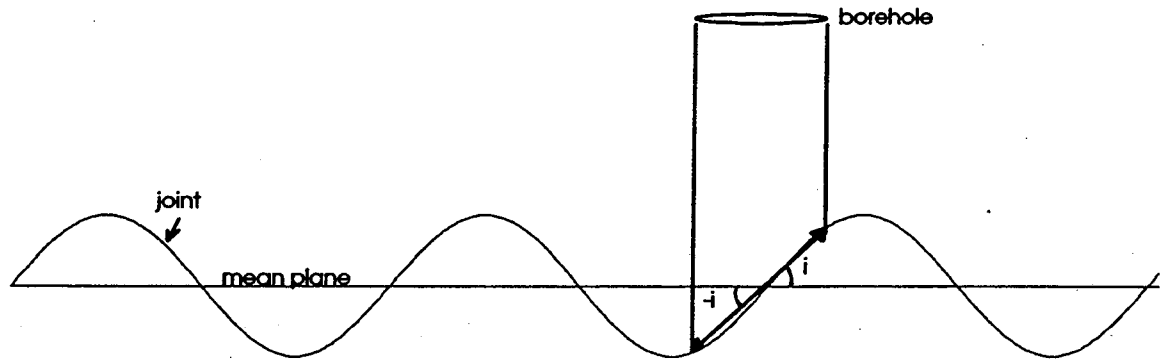


**Fig. 4.8(b.4): Anisotropy curve for upper profile of joint 10-1 at a scale of 49.5 to 50.5 mm**



used to select the scale of interest, as explained earlier for the use of Rengers envelope. For purposes of anisotropy curve interpretation herein, the average block size or joint length, is assumed to be 1 m so that surface undulations at scales of less than 1 cm are considered to be roughness that contributes to peak shear strength while undulations at scales larger than 1 cm are considered to be part of the joint's waviness which does not influence peak shear strength.

The anisotropy curves shown in Figure 4.8 are symmetric about azimuth 180, since each vector that connects profile points produces a positive and negative dilation angle in opposite directions, as explained in Section 4.2.2. In Figure 4.8(a), the dilation angles appear to be close to isotropic. However, there are azimuth intervals, such as between 50 and 100, in which the dilation angles are clearly lower than in other directions. In contrast to the small scales, the larger scales define a clear pattern of anisotropy. The larger scales show the dilation angles to be about 20 degrees towards the dip direction and its opposite, while the dilation angle is shown to be zero towards the strike directions. The dilation angles between these four directions have intermediate values of the dilation angle. This pattern fits a model consisting of a nearly planar surface with the same dip direction as the joint, but with a slightly larger dip as shown in Figure 4.8(c). Thus the undulation about the mean plane shown in Figure 4.8(a) at the larger scales could be the joint waviness. However, the anisotropy curve may also be reflecting an error in the dip of the mean joint plane. The anisotropy curve for the upper joint wall shown in Figure 4.8(b) indicates a more isotropic surface roughness at the small scales compared to the lower joint wall. The waviness at larger scales on the upper joint wall resembles the waviness of the lower joint wall.



Anisotropy curves for this undulating joint surface are shown below for two dip directions. The maximum roughness angle is observed along the dip direction and the roughness angle is zero along the strike. Intermediate values of the roughness angle are observed in between these directions.

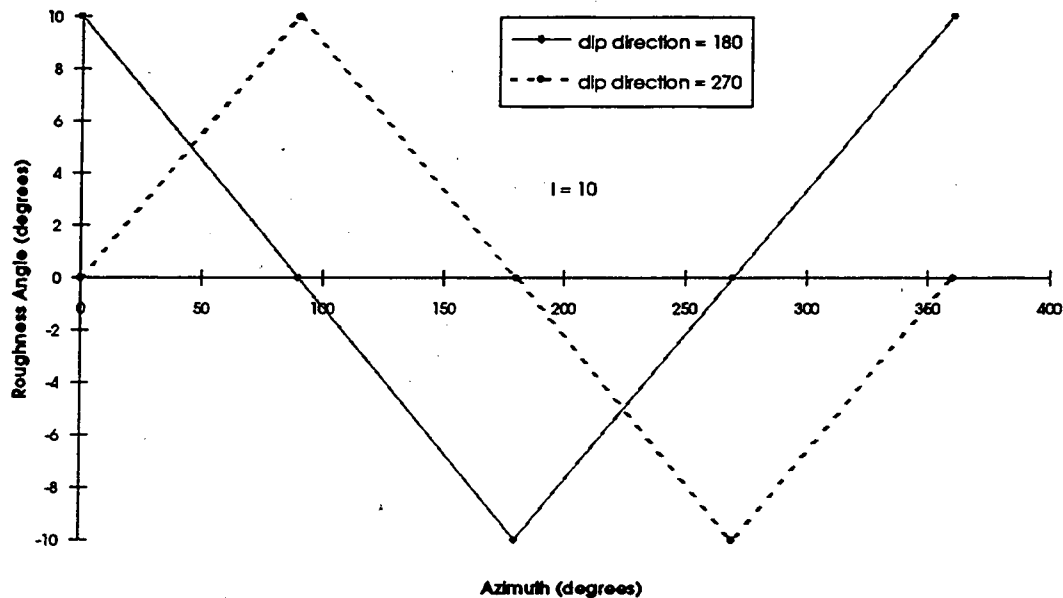


Figure 4.8(c): Interpretation of joint waviness from anisotropy curves

#### 4.3.4 Anisotropy of borehole 3-5 joints

Anisotropy curves were constructed for the opposing joints profiles from borehole 3-5. Two scales of  $5 \text{ mm} \pm .5$  and  $10 \text{ mm} \pm .5$  were used to analyze roughness anisotropy. Two other scales of  $34 \text{ mm} \pm .5$  and  $50 \text{ mm} \pm .5$  were

used to assess waviness anisotropy. Some of the anisotropy curves analyzed from borehole 3-5 are given in Appendix F as examples. Table 4.1 summarizes the findings of this anisotropy analysis.

Table 4.1 shows that most of the joint surfaces are anisotropic at the larger scales corresponding to waviness. Very few joints are isotropic at any scale, but many joints are close to being isotropic at the smaller scales and especially at the smallest scale. In Table 4.1, the joints labeled as being close to isotropic typically show lower roughness angles in one or two narrow azimuth bands. If a larger interval were used to specify the scale of interest in the anisotropy analysis program, it is possible the additional  $(i, a)$  samples would tend to make the anisotropy curve appear more isotropic. Also, judging from the trend of decreasing anisotropy at smaller scales, analysis of anisotropy at scales less than 5 mm would probably show even more roughness isotropy than seen at the smaller scales in Table 4.1.

The data in Table 4.1 show that when the joint surface is close to being isotropic, it is usually so at small scales and exhibits anisotropy with increasing scale. This characteristic is probably due to waviness at larger scales. Examples of this are seen in the case of joints 13-1, 15-3, 19-2, 19-3 and 21-2. There is a disagreement between this observation and the finding of Harrison and Goodfellow (1993) who found anisotropy to decrease with increasing scale. This disagreement is probably due to the differences in scales used here and in Harrison and Goodfellow's studies where the scales used ranged from 75 mm to 200 mm. The scales used here are reflecting an increase in the anisotropy due to a transition from roughness to waviness, while the large scales used by Harrison and Goodfellow will tend to show decreasing anisotropy as the wavelength of the waviness is exceeded. However, there are joints in borehole 3-5 that follow the trend described by Harrison and Goodfellow even at the



smaller scales used in this thesis. Joint 20-2 and the lower profile of joint 19-1 are such examples.

Table 4.1: Anisotropy analysis results for joints of borehole 3-5

| Joint                                              | Lower Profile Scales in mm |          |           |           | Upper Profile Scales in mm |          |           |           |
|----------------------------------------------------|----------------------------|----------|-----------|-----------|----------------------------|----------|-----------|-----------|
| Label                                              | 4.5-5.5                    | 9.5-10.5 | 34.5-35.5 | 49.5-50.5 | 4.5-5.5                    | 9.5-10.5 | 34.5-35.5 | 49.5-50.5 |
| 9-1                                                | NI                         | NI       | A         | A         | NI                         | A        | A         | A         |
| 10-1                                               | NI                         | NI       | A         | A         | NI                         | NI       | A         | A         |
| 10-2                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 10-3                                               | NI                         | A        | A         | A         | NI                         | A        | A         | A         |
| 10-4                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 11-1                                               | A                          | A        | A         | A         | NI                         | NI       | A         | A         |
| 13-1                                               | I                          | NI       | A         | A         | NI                         | NI       | A         | A         |
| 13-2                                               | NI                         | A        | A         | A         | NI                         | NI       | NI        | NI        |
| 14-1                                               | A                          | A        | A         | A         | NI                         | NI       | A         | A         |
| 14-2                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 14-3                                               | NI                         | A        | A         | A         | A                          | A        | A         | A         |
| 14-4                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 15-1                                               | NI                         | NI       | NI        | NI        | NI                         | NI       | A         | A         |
| 15-2                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 15-3                                               | NI                         | A        | A         | A         | NI                         | A        | A         | A         |
| 15-4                                               | NI                         | NI       | I         | I         | A                          | A        | A         | A         |
| 15-5                                               | A                          | A        | A         | A         | I                          | A        | A         | A         |
| 17-1                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 17-2                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 18-1                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 19-1                                               | A                          | A        | NI        | NI        | NI                         | NI       | NI        | NI        |
| 19-2                                               | NI                         | A        | A         | A         | NI                         | A        | A         | A         |
| 19-3                                               | NI                         | NI       | A         | A         | NI                         | NI       | A         | A         |
| 19-4                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 20-1                                               | A                          | A        | A         | A         | NI                         | NI       | A         | A         |
| 20-2                                               | A                          | A        | NI        | NI        | A                          | A        | NI        | NI        |
| 20-3                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 21-1                                               | A                          | A        | A         | A         | A                          | A        | A         | A         |
| 21-2                                               | I                          | NI       | A         | A         | I                          | I        | A         | A         |
| 21-3                                               | NI                         | A        | NI        | NI        | I                          | NI       | NI        | NI        |
| A: anisotropic; I: isotropic; NI: nearly isotropic |                            |          |           |           |                            |          |           |           |

The anisotropy curves at the smaller scales do not fall into a clear pattern that would allow a surface topography to be interpreted. With increasing scale, the anisotropy curves begin to show patterns. Most of the joints show a near

planar waviness towards the dip direction as in the case of joint 10-1 described in Section 4.3.3. From this observation, it appears joint waviness usually involves undulations about the mean plane towards the dip direction. Table 4.2 lists the interpretation of waviness forms made from the anisotropy curves for borehole 3-5 joints.

**Table 4.2: Form of anisotropy at larger scales in borehole 3-5 joints**

| Joint | Upper Profile | Lower Profile | Joint | Upper Profile | Lower Profile |
|-------|---------------|---------------|-------|---------------|---------------|
| 9-1   | near plane    | near plane    | 15-4  | near plane    | smooth        |
| 10-1  | near plane    | near plane    | 15-5  | near plane    | near plane    |
| 10-2  | complex       | complex       | 17-1  | near plane    | near plane    |
| 10-3  | complex       | complex       | 17-2  | near plane    | near plane    |
| 10-4  | complex       | complex       | 18-1  | near plane    | complex       |
| 11-1  | complex       | complex       | 19-1  | smooth        | smooth        |
| 13-1  | near plane    | smooth        | 19-2  | near plane    | near plane    |
| 13-2  | near plane    | near plane    | 19-3  | complex       | near plane    |
| 14-1  | smooth        | complex       | 19-4  | near plane    | near plane    |
| 14-2  | near plane    | near plane    | 20-1  | near plane    | near plane    |
| 14-3  | complex       | complex       | 20-2  | near plane    | near plane    |
| 14-4  | complex       | complex       | 20-3  | near plane    | near plane    |
| 15-1  | near plane    | near plane    | 21-1  | near plane    | near plane    |
| 15-2  | near plane    | near plane    | 21-2  | near plane    | near plane    |
| 15-3  | complex       | complex       | 21-3  | smooth        | smooth        |

#### **4.4 Unrolling profiles into two dimensions**

The roughness profiles extracted from the BSS image are samples of points from opposing three dimensional curved surfaces of the joint walls. These samples lie along curves determined by the intersection of the borehole with the joint walls. Unrolled two dimensional opposing joint profiles are desirable since the methods of analyzing joint shear strength, described later in this chapter, require a two dimensional representation of the opposing joint profiles. Prior to unrolling, pairs of opposing profile points have to be defined. This pairing produces measurements of the joint aperture. The aperture measurement method is explained before going on to the discussion of profile unrolling.

#### 4.4.1 Aperture measurement

Joint aperture is defined by the magnitude of the vector connecting points on the lower profile to points on the upper profile. The vector connecting opposing profile points is directed normal to the mean joint plane. When the mean joint plane has a dip greater than  $0^\circ$  and less than  $90^\circ$ , and the borehole is vertical, the aperture vector originating on a lower profile point will generally not intersect any upper profile point. This situation is shown in Figure 4.9. Since the majority of joints intersected by the borehole will have a geometric configuration similar to Figure 4.9, measurement of joint aperture requires some method of accounting for this problem.

Figure 4.9 shows two smooth opposing joint walls with the same orientation being intersected by a vertical borehole. The intersection produces traces of the borehole wall in the upper and lower profiles. These traces, in discrete form, would be the equivalent of the BSS profiles. The true aperture of the joint is shown by the vector  $\bar{n}$  connecting the lower profile point  $o$  to its true opposing point  $a$ . However, in the BSS profiles, the vector  $\bar{n}$  cannot be found since point  $a$  does not lie on the curve defined by the intersection of the borehole with the upper joint wall. Since the true aperture cannot be found, one of two alternative approaches may be taken to estimate  $\bar{n}$ . One approach involves correction of an apparent aperture vector such as  $\bar{b}$ , which is directed vertically parallel to the borehole axis:

$$\|\bar{n}\| = \|\bar{b}\| \cos \theta \quad (4.5)$$

The apparent aperture approach assumes the upper joint wall is a smooth plane between points  $b$  and  $a$  as shown in Figure 4.9. This assumption contradicts the



entire exercise of measuring roughness and apertures where deviations from a mean plane are being sought. The other approach to aperture measurement uses the vector  $\bar{n}_d$  as the estimate of  $\bar{n}$ . Point  $p$  on vector  $\bar{n}_d$  is chosen so that the error vector  $\bar{e}$  is a minimum along one or more segments of the profile. This second approach, based on error minimization, is used in this thesis in order to observe magnitudes of the aperture measurement error for real joints.

#### 4.4.1.1 Synthetic experiment of aperture measurement error

A synthetic experiment was carried out to study the sensitivity of the aperture measurement error to the geometric parameters defining Figure 4.9. A program was written to generate upper and lower profile points by intersecting a cylinder with two parallel planes separated by a constant true aperture. The borehole diameter, orientation of the planes and the constant true aperture are user defined in the program. Once the upper and lower profile points are generated, the program proceeds with aperture measurement beginning with the highest profile point on the lower profile (this point will be  $180^\circ$  from the dip direction). Using the highest profile point as point  $o$ , the program finds point  $a$  as

$$a_i = o_i + \bar{n}_i \delta \quad (4.6)$$

where  $i = x, y, z$  and  $\delta$  is the true aperture

Point  $p$  is found by finding a point on the upper profile that lies on a plane (G) perpendicular to both joint planes and having the same strike as the joint planes. Since both  $\bar{n}$  and  $\bar{e}$  lie on plane G, its coefficients can be found as

$$G(a, b, c) = \bar{e} \times \bar{n} \quad (4.7)$$

The vector  $\bar{e}$  in Eqn. (4.3) is horizontal as it lies along the strike of plane G so  $e_z = 0$ . The other two unit components of  $\bar{e}$  can be found as

$$\begin{aligned} e_x &= \sin(\alpha + 90) \\ e_y &= \cos(\alpha + 90) \end{aligned} \quad (4.8)$$

where  $\alpha$  is the dip direction of the opposing planes

Once point  $p$  is found in this way, the vectors  $\bar{n}_d$  and  $\bar{e}$  are found and their magnitudes stored as one aperture measurement. The point  $o$  is then moved to the next lower profile point. Since the problem is symmetric about the dip direction, it does not matter which side of the dip direction is chosen as the next location of point  $o$ . The procedure of finding points  $a$  and  $p$  is then repeated. The search for point  $p$  that satisfies the equation of plane G always begins from the highest upper profile point and proceeds sequentially towards the dip direction. Upper profile points that have already been paired with a lower profile point are not used in the search. The first upper profile point found to satisfy the equation for plane G is selected as point  $p$ .

Figure 4.10 shows the aperture measurement error for a case with a dip of  $45^\circ$  and a borehole radius of 10 mm. The error is a minimum at lower profile points with depths in between the high and low profile point depths. The error jumps to a maximum at the high and low profile depth points which lie along the dip direction vector. The errors are symmetrical about the strike as well as the dip direction lines (Figure 4.10 shows apertures measured between  $0^\circ$  and  $180^\circ$  only -- the data from  $180^\circ$  to  $360^\circ$  produce identical results due to the symmetry). The aperture pairs represented in Figure 4.10 do not include some lower profile points towards the dip direction, as plane G for these points do not intersect any upper profile points.

Other cases with decreasing values of dip were also analyzed. The results for these other cases were similar to Figure 4.10 and are given in Appendix G. These results show that the aperture measurement errors decrease with decreasing dip. The results from all the cases are summarized in Figure

4.11. Analysis of the results shown in Appendix G and Figure 4.11 show that while aperture measurement error increases with increasing dip, since there are more opposing profile points in joints with higher dips, the length of consecutive opposing pairs with errors within a small limit remains almost constant.

Figure 4.12 shows the results for a case with a dip of  $45^\circ$  and a borehole radius of 76 mm. The only difference in the results, in comparison to the cases with a smaller borehole radius, is the increase in the cumulative distance between consecutive opposing pairs with errors close to zero.

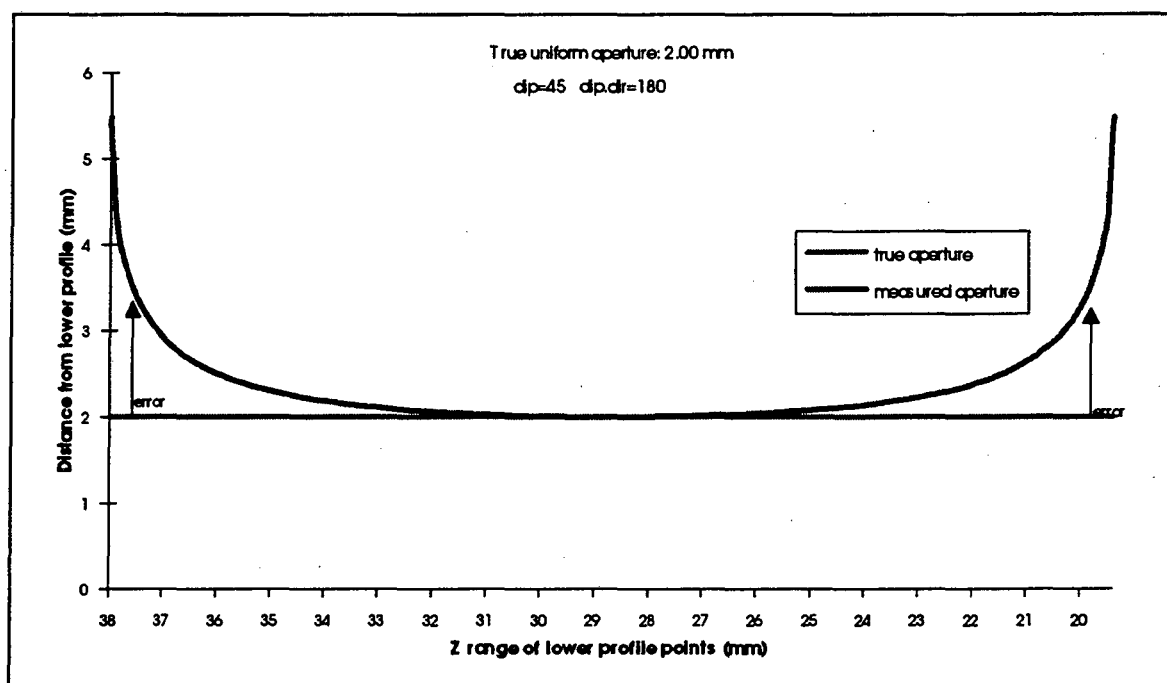


Figure 4.10: Synthetic aperture measurement errors for  $45^\circ$  dip

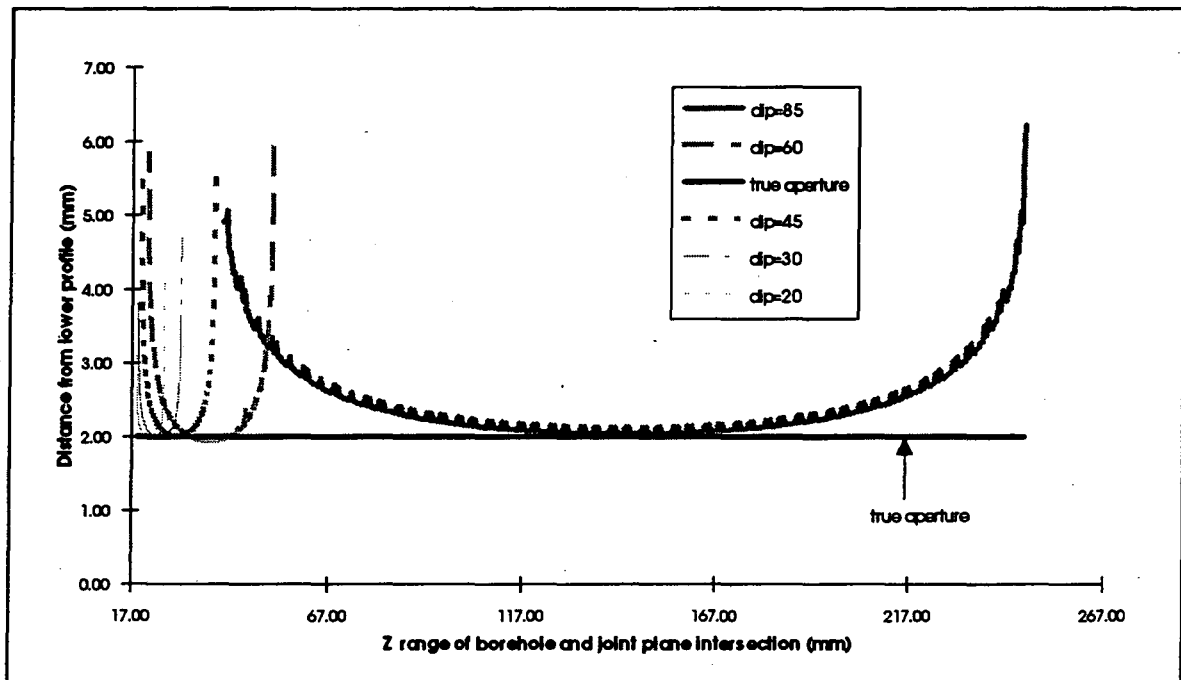


Figure 4.11: Synthetic aperture measurement errors for all dips

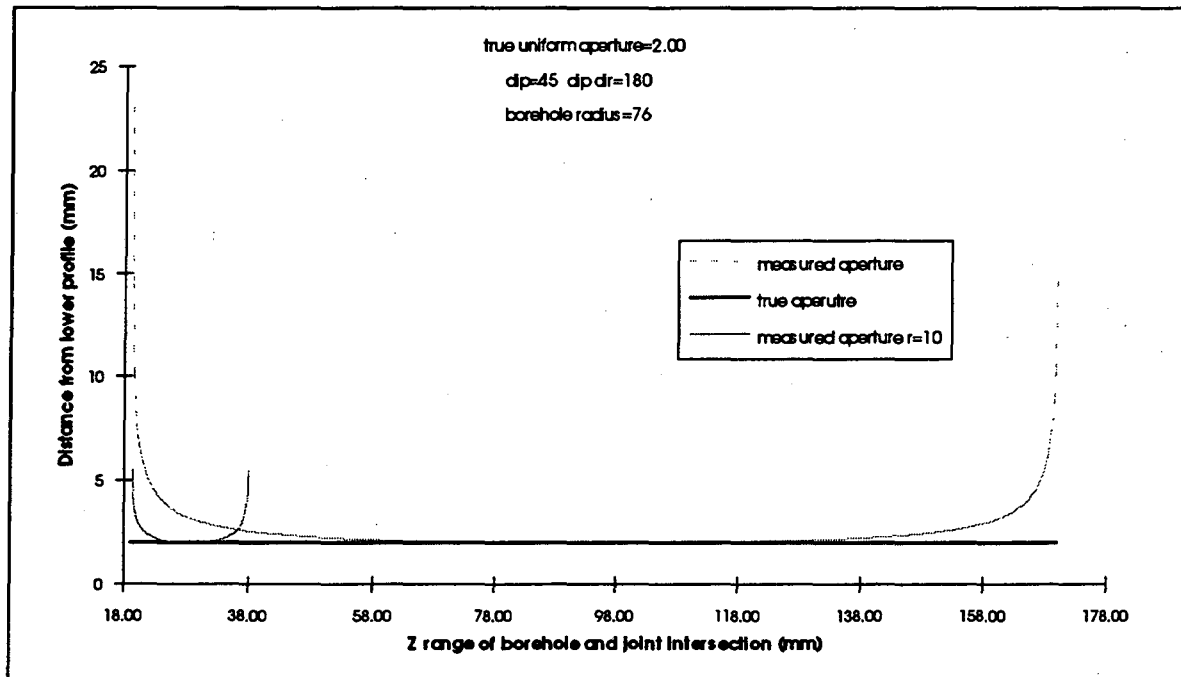


Figure 4.12: Synthetic aperture measurement errors for a large borehole



#### 4.4.1.2 Apertures and measurement errors on joints in borehole 3-5

The method of pairing opposing profile points of the real joint profiles from BSS images is the same as the procedure described above for the synthetic experiment except for two differences. The first difference is that in the case of the real data, point  $p$  is found first using the intersection of plane G with the upper profile data. Plane G is found using Eqn. (4.3). Then point  $a$  is found using Eqn. (4.2), where the distance  $d$  is calculated as the distance between the mean orientation plane passing through point  $p$  and a parallel plane passing through point  $o$ . The other difference in the aperture analysis for the real data in comparison to the synthetic data is that the pairing is done for all lower profile points on both sides of the dip direction vector. This is because unlike the synthetic data, which was symmetric about the dip direction vector, the real data is generally not symmetric about the dip direction vector. Note that the computed error vector is only an estimate of the true error.

The procedure for pairing opposing profile points and finding apertures of real BSS profiles was coded in a program. Synthetic upper and lower profiles generated for smooth joints, separated by a constant true aperture of 3.54 mm, were piped to the program for verification. The smooth joint had a dip of  $45^\circ$  towards  $270^\circ$ . The aperture measurements produced by the program are given in Appendix H. As expected, the measurement errors are highest in the dip direction and lowest along the strike directions. When the error is close to zero, the measured aperture is very close to the true aperture.

Apertures of joint 13-1 from borehole 3-5 were analyzed using the program for pairing opposing profile points of real BSS data. Joint 13-1 dips  $20^\circ$  towards  $254^\circ$ . Figure 4.13 shows the result of this analysis. The estimated measurement errors are usually less than 2 mm and the apertures range from 1 mm to about 8 mm. As expected, the apertures and estimated measurement

errors in the dip and reverse directions are unusually high. The scanner resolution, about 0.5 mm here, can be used as the upper limit of acceptable error for aperture measurements. Examples of aperture measurements of other joints in borehole 3-5 are presented in Appendix I.

#### 4.4.2 Unrolling procedure

As mentioned before, it is desirable to transform the BSS opposing profiles into a two dimensional sample for mechanical analysis of joint shearing strength. This transformation utilizes the pairing of opposing profile points described in the last section.

The transformation of the BSS profiles is done with respect to a reference datum plane placed below the lowest profile point on the lower profile. This datum plane has the same orientation as the mean orientation plane of the joints. Pairs of opposing profile points are projected onto the datum plane along the normal direction of the datum plane to find the ordinates of the unrolled opposing profiles:

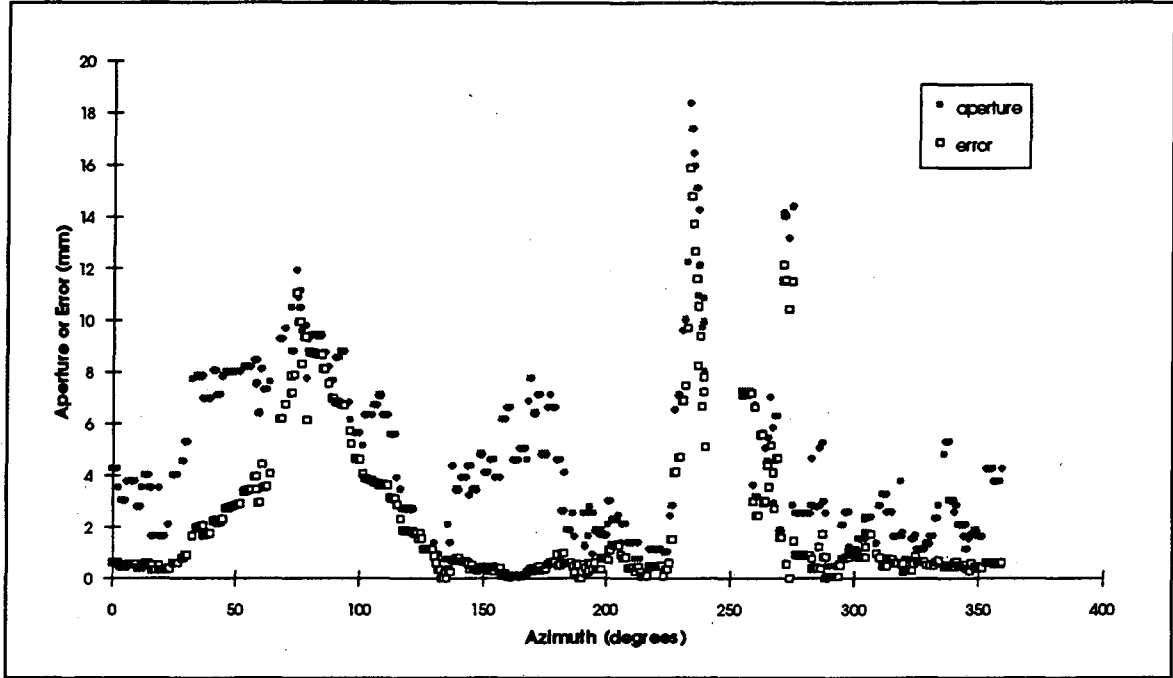


Figure 4.13: Apertures and measurement errors for joint 13-1

$$y_l = \frac{\|\bar{n} \cdot \bar{d}\|}{\|\bar{n}\|}$$

$$y_u = y_l + \|\bar{n}d\| \quad (4.9)$$

where  $y_l$  and  $y_u$  are the upper and lower abscissa respectively,  $\bar{n}$  is the joint normal,  $\bar{n}d$  is the aperture for the pair and  $\bar{d}$  is a vector between the lower profile point of the pair and the lowest point on the lower profile

The location of the first opposing profile pair's projection on the datum plane defines the origin of the two dimensional sample. The distance between consecutive projection points on the datum plane is the increment along the abscissa:

$$\Delta x = \|\bar{d}_{ij}\| \quad (4.10)$$

where  $\Delta x$  is the increment along the abscissa between two consecutive projection points  $i$  and  $j$  and  $\bar{d}_{ij}$  is the vector between these points.

Consecutive  $\Delta x$  increments are summed during each projection of opposing profile pairs to produce a series of triplets  $(x, y_l, y_u)$  that comprises the unrolled two dimensional sample of the joint. The estimated error from pairing opposing profiles can be used to decide to include only those pairs having errors less than a prescribed value in the unrolling. Any lower profile point can be chosen as the first point for unrolling. The lowest lower profile point in the decreasing azimuth direction having an acceptable pairing error is used as the initial point in the unrolling procedure here. Regardless of which point in the lower profile is chosen as the initial unrolled sample point, there will be at least one discontinuity in the unrolled sample. The first discontinuity occurs in the unrolling of opposing pairs towards the dip direction. As explained in Section 4.4.1.1, the aperture measurement error will be very high in the dip direction. Usually, this error will usually be larger than the tolerance used in accepting opposing pairs for the unrolling. Thus a series of consecutive opposing pairs will be skipped and the unrolled profile will have a large  $x$  increment. For instance, in a case where the mean plane dips  $45^\circ$  towards  $270^\circ$ , opposing pairs from  $268^\circ$  to  $272^\circ$  may be skipped and pairs from  $267^\circ$  and  $273^\circ$  may be connected as consecutive unrolled profile points. The second discontinuity in the unrolled profile occurs in the direction opposite to the dip direction for the same reason as in the case of the discontinuity in the dip direction. One of these two discontinuities can be avoided by starting the unrolling at either side of the dip direction vector. The unrolling is started so as avoid the first discontinuity here.

The procedure described above was coded in a program for pairing opposing profile points and unrolling the opposing profiles. The test joint dipping at  $45^{\circ}$  towards  $270^{\circ}$  described in Section 4.4.1.2 for verifying the aperture measurement part of this same program was used again to verify the unrolling part. The unrolled opposing profiles produced by this program are shown in Appendix H. As expected, the unrolled profiles are straight lines separated by a constant aperture of about 3.54 mm. The large gap in the data between 39 mm and 120 mm is due to the discontinuity discussed earlier in the direction opposite to the dip direction. The discontinuity is very large here because the dip of the test joint is fairly high.

The unrolling of opposing BSS derived roughness profiles is valid only at scales at which the roughness profile is isotropic. Since scale represents the displacement distance during shearing, unrolled roughness profiles provide a valid sample for shear displacement analysis up to a limiting displacement defined by the largest scale at which the joint is found to be isotropic. This limit has to be established using the anisotropy analysis program as discussed earlier.

#### 4.4.3 Unrolled profiles for borehole 3-5 joints

Unrolled profiles for joints in borehole 3-5 were obtained using unroll.c. Figure 4.14 shows the unrolled profile for joint 13-1 at an acceptable aperture measurement error level of 2 mm. Decreasing the acceptable error leads to a smoother profile, as fewer opposing pairs are included in the unrolled profiles. The magnitude of the pairing errors are also shown below the profile points in Figure 4.14. The discontinuity in the direction opposite to the dip direction occurs around 160-225 mm along the abscissa. Examples of unrolled profiles for other joints from borehole 3-5 are presented in Appendix J. One of these unrolled profiles can be obtained using the program discussed above on a 486

compatible PC in about 10 minutes once the roughness profile discussed in Chapter 3 is available.

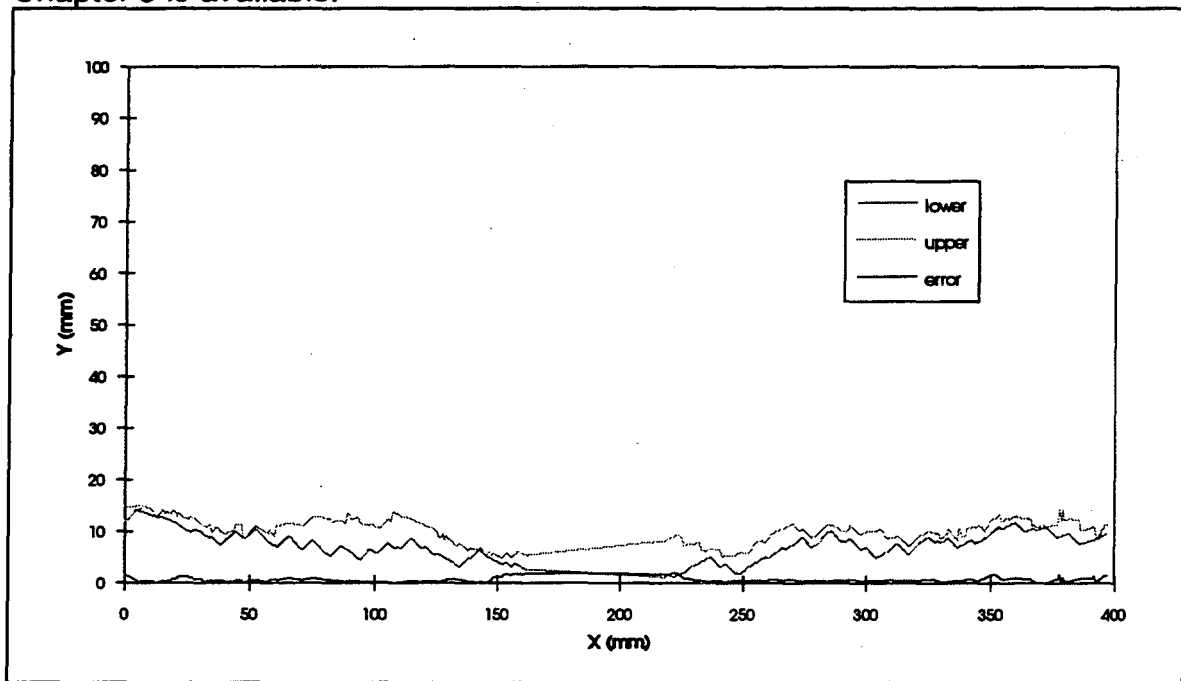


Figure 4.14: Unrolled opposing profiles for joint 13-1

## CHAPTER 5

### ANALYSIS OF SHEAR DISPLACEMENT BEHAVIOR

#### 5.1 Kinematic displacement dilation analysis

As discussed in Section 4.2.1, joint roughness profiles control peak shear strength and volume change behavior during shear displacement under low normal stress conditions. A new analysis for these joint characteristics utilizing opposing joint profiles is described in this chapter. The new analysis is applied to in-situ BSS opposing joint profiles.

##### 5.1.1 Background

A method of deriving the dilatancy and shear stress-shear deformation curves, using Rengers envelope, for a perfectly mated joint was described by Schneider (1976). Schneider's method is illustrated in Figure 5.1. The dilatancy curve locus is defined by

$$v = u \tan i(u) \quad (5.1)$$

where  $u$  is the displacement,  $i(u)$  is the dilation angle at  $u$ , and  $v$  is the dilation at  $u$ .

The shear stress-shear deformation curve is constructed using

$$\tau(u) = \sigma \tan[\phi_r + i_{\tan}(u)] \quad (5.2)$$

where  $i_{\tan}(u)$  is the inclination of the tangent to the dilatancy curve at  $u$ ,  $\phi_r$  is the residual friction angle,  $\sigma$  is the normal stress across the joint and  $\tau(u)$  is the shear stress at  $u$ .

In order to evaluate the accuracy of Schneider's method, an alternate dilatancy curve for the roughness profile of Figure 5.1 was constructed by hand, tracing the actual dilatancy of a plastic model of the upper block during right lateral shearing. The model used in this kinematic simulation of joint shearing consisted of blocks cut out of plastic separated by the roughness profile shown in Figure 5.1. Only displacements parallel and perpendicular to the mean joint plane were allowed during the simulated shearing process -- no rotation occurred. The results from this simulation are presented in Figure 5.2 and Figure 5.4 along with the results of Schneider's analysis.

Figure 5.2 shows that the dilatancy curve from Schneider's method agrees with the simulated dilatancy curve over most of the displacement range (i.e. from 0 to 15 mm). As long as the basic assumption that the maximum dilation angle (as given in Rengers envelope) at any displacement controls dilation is true, Schneider's method produces accurate results. This assumption holds when the opposing profiles are perfectly mated, but is generally violated when apertures are not zero along the entire length of the opposing profiles, regardless of whether the opposing profiles are mirror images of each other or not. The dilatancy curves for the non-mated upper profiles  $P_1$ ,  $P_2$  and  $P_3$  in Figure 5.2 illustrate this fact. Figure 5.3 shows the upper profiles  $P_1$ ,  $P_2$  and  $P_3$ . The lower profiles for all the cases shown in Figure 5.2 are the same as the profiles of the perfectly mated case shown in Figure 5.1. The upper profiles  $P_1$ ,  $P_2$  and  $P_3$  consist of two spikes each located at different spacings. By carrying out the kinematic shear displacement simulation for the three unmated cases of Figure 5.2, it was observed that the location and amplitude of the upper profile spikes determine which asperities of the lower profile may influence dilation as displacement proceeds. The resulting asperity sampling sequence is not constrained to follow the pattern of Rengers envelope with increasing



displacement increments and infact does not do so for the unmated cases plotted in Figure 5.2. Thus, Schneider's method is not able to account for the dilatancy of unmated opposing profiles.

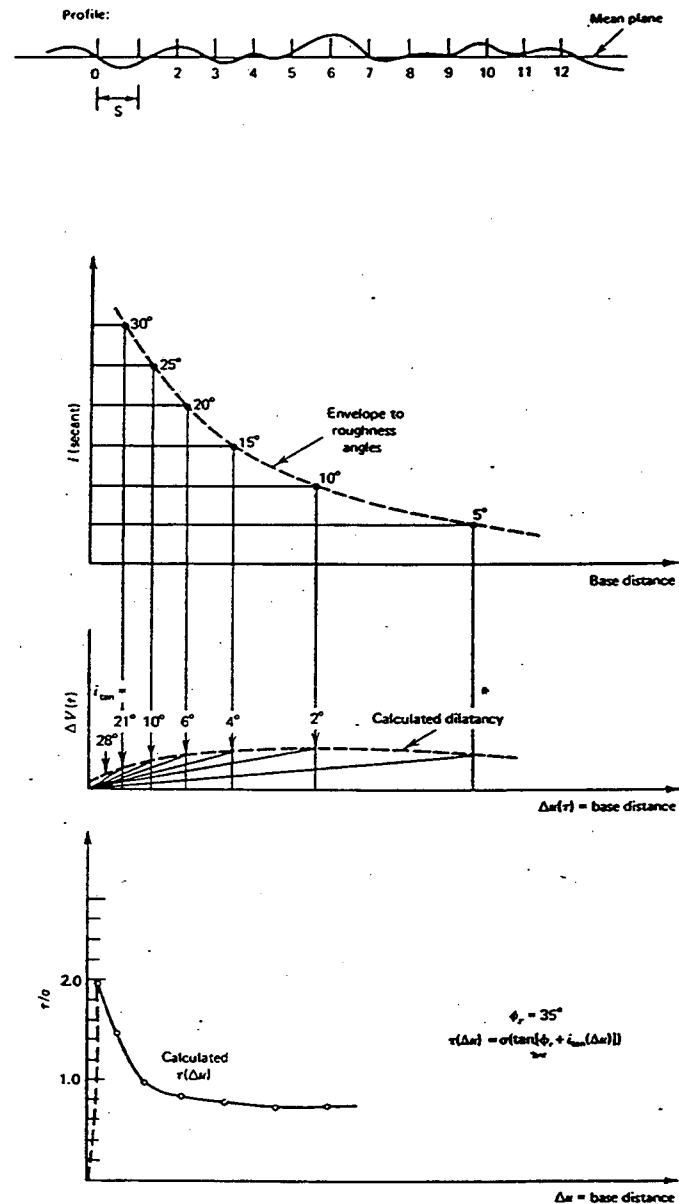
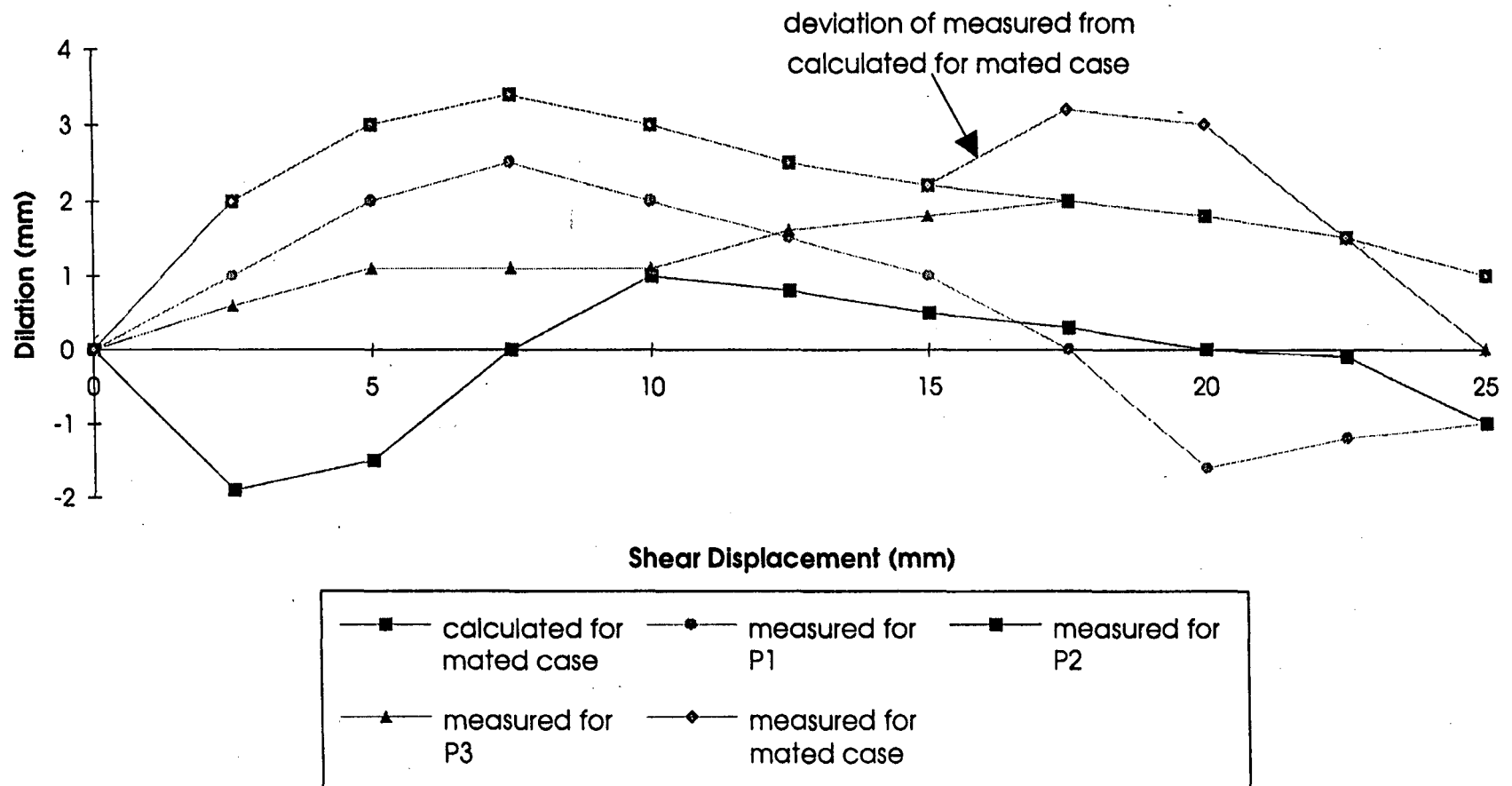


Figure 5.1: Schneider's method of constructing dilatancy and shear-stress shear deformation curves (after Goodman, 1989)

Figure 5.2: Comparison of simulated and calculated dilatancy curves



The sampling scheme that defines which lower profile points may influence the dilatancy over the next increment of displacement is determined by the geometry of the opposing profiles, i.e. the contact points. When the opposing profiles are perfectly mated, the upper profile samples all points on the lower profile. In this case, since the entire lower profile is available for sampling, the lower profile slope that determines the dilatancy rate over the next displacement increment will be the same as the roughness angle in Rengers envelope,

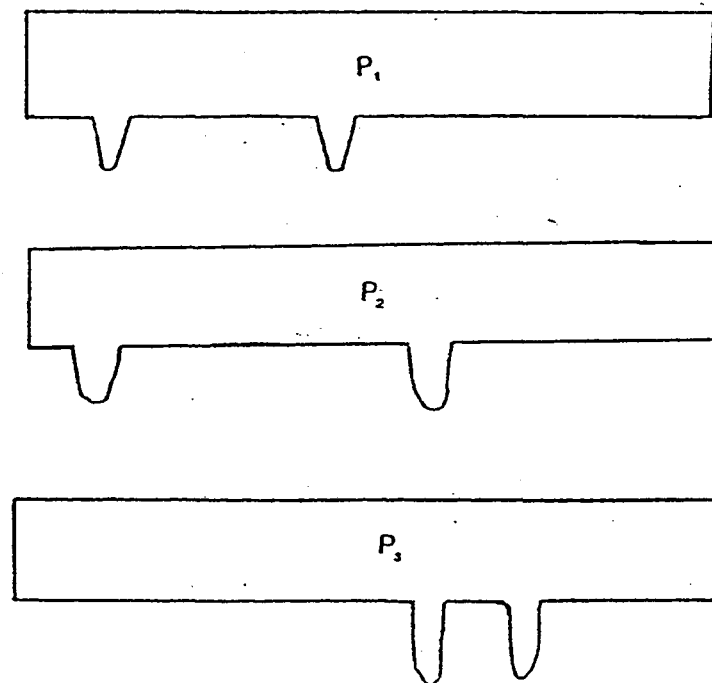


Figure 5.3: Unmated upper profiles

provided the displacement increment is small. In contrast to the perfectly mated case, if the upper profile consisted of only one spike, the dilatancy curve would be a reproduction of the roughness profile. Two spikes on the upper profile produce a dilatancy curve determined by the larger of the two asperity slopes sampled by the upper profile at successive displacements. Similarly, dilatancy in

real joints will be the result of samples of lower profile slopes at all contacting points at each displacement increment.

The kinematic simulation experiment using unmated profiles also showed that the rate of dilatancy at each increment of displacement (and hence the dilatancy curve as well) is equal to the steepest slope among slopes of lower profile points sampled by the upper profile at each increment of displacement. Thus, Eqns. (5.1) and (5.2) are replaced by the following expressions which work with mated and unmated opposing profiles:

$$i(u) = \max \left[ \frac{dy}{dx} \right] \forall x \text{ where } a = 0 \quad (5.3)$$

where  $\frac{dy}{dx}$  is the slope of the lower profile and at  $x$  and  $a$  is the aperture at

$x$ . Note: the symbol  $\forall$  means 'for all.'

$$v(u) = \max \left[ \frac{dy}{dx} \right] du \quad (5.4)$$

where  $\max \left[ \frac{dy}{dx} \right]$  is evaluated at all  $x$  where  $a = 0$  and  $du$  is the displacement increment.

$$\tau(u) = \sigma \left\{ \tan \phi_r + \max \left[ \frac{dy}{dx} \right] \right\} \quad (5.5)$$

where  $\max \left[ \frac{dy}{dx} \right]$  is evaluated at all  $x$  where  $a = 0$ .

Eqn. (5.3) disagrees with the comparison of Rengers dilation angles and the tangent to the dilation curve in Figure 5.1 since this figure shows these angles to be unequal. The reason for the disagreement is because the dilation angles

measured in constructing Rengers envelope are considered to apply at the end of the displacement distance connecting points on the concave roughness profile shown in Figure 5.1. The concavity of the roughness profile makes the actual dilation angle at the end of the displacement distance smaller than the calculated dilation angle. Thus the tangent to the dilation curve in Figure 5.1 is lower than the dilation angle shown in Rengers envelope for that displacement. At large displacements the disagreement is also influenced by the unmated dilatancy behavior described above.

The results shown in Figure 5.2 show that changes in the opposing profiles can cause changes in the amount of dilation and the displacement at which peak dilation occurs. For instance, in the case of upper profile  $P_2$ , the initial location of the spikes on parts of the lower profile having negative slopes results in contraction up to a displacement of 7.5 mm. The maximum dilation developed by  $P_2$  is only 1 mm compared to the peak dilation of 3.4 mm in the case of the perfectly mated joints. Also, the peak dilation of  $P_2$  occurs at a displacement of 10 mm while the perfectly mated joints show a peak dilation at 7.5 mm.

Figure 5.2 shows that the dilation curve for the perfectly mated case is an envelope to all other unmated cases. This follows from the preceding discussion of how the perfectly mated joint can take advantage of the highest roughness angle possible while unmated joints may not be able to do so. In other words, the perfectly mated upper profile utilizes the full dilation potential offered by the lower surface. The perfectly mated joint will always be the envelope to unmated joint dilation curves. Thus the perfectly mated joint is always the strongest in terms of strength due to dilatancy. Grouting an unmated joint such that apertures are reduced to zero raises joint strength by forcing maximum dilatancy from the joint. Alternately, if all apertures are not reduced to zero, the effectiveness of grouting

can be evaluated by analyzing the increase in dilatancy or shear strength caused by changes in the opposing profiles and apertures due to grouting. The analysis can be done using the method described in the next section.

The shear stress-shear displacement curves for the mated and unmated cases described above are shown in Figure 5.4. The curves in Figure 5.4 were constructed using Eqn. (5.3) with  $\phi_r = 35^\circ$ . The peak value of  $i_{\tan}$  decreased, in comparison to the perfectly mated case, by 7% for  $P_1$ , by 0% for  $P_2$  and by 60% for  $P_3$ . The reason  $P_2$  had the same  $i_{\tan}$  value as the perfectly mated case is that the location of the spikes in  $P_2$  happened to sample the asperity on the lower profile having the largest slope. This did not happen in the other unmated cases and hence the loss in peak strength. Thus, the peak strength of unmated joints may be significantly lower than that predicted by Schneider's method using a single profile. Engineering design based on a peak shear strength given by Eqn. (4.1) should be based on  $i(u)$  from Eqn. (5.3) instead of Rengers envelope to avoid overestimating the dilation angle.

#### 5.1.2 Improved method using opposing joint roughness profiles

A new procedure of analyzing dilatancy and shear stress-shear deformation behavior can be developed utilizing the findings of the kinematic shearing experiment. This new procedure assumes there is no shearing through joints and that there is no rotation about the mean joint plane during shear displacement. The procedure is as follows:

- (1) Find the aperture at all opposing profile points.
- (2) At each opposing profile point where  $a = 0$ , find  $i(\Delta u)$  using Eqn. (5.3) for the shearing direction of interest.
- (3) Increment displacement by  $\Delta u$  and compute new coordinates of all upper profile points as

$$(x_i)_{u+\Delta u} = (x_i)_u + \Delta u \quad \forall \quad i=1..n \quad (5.6)$$

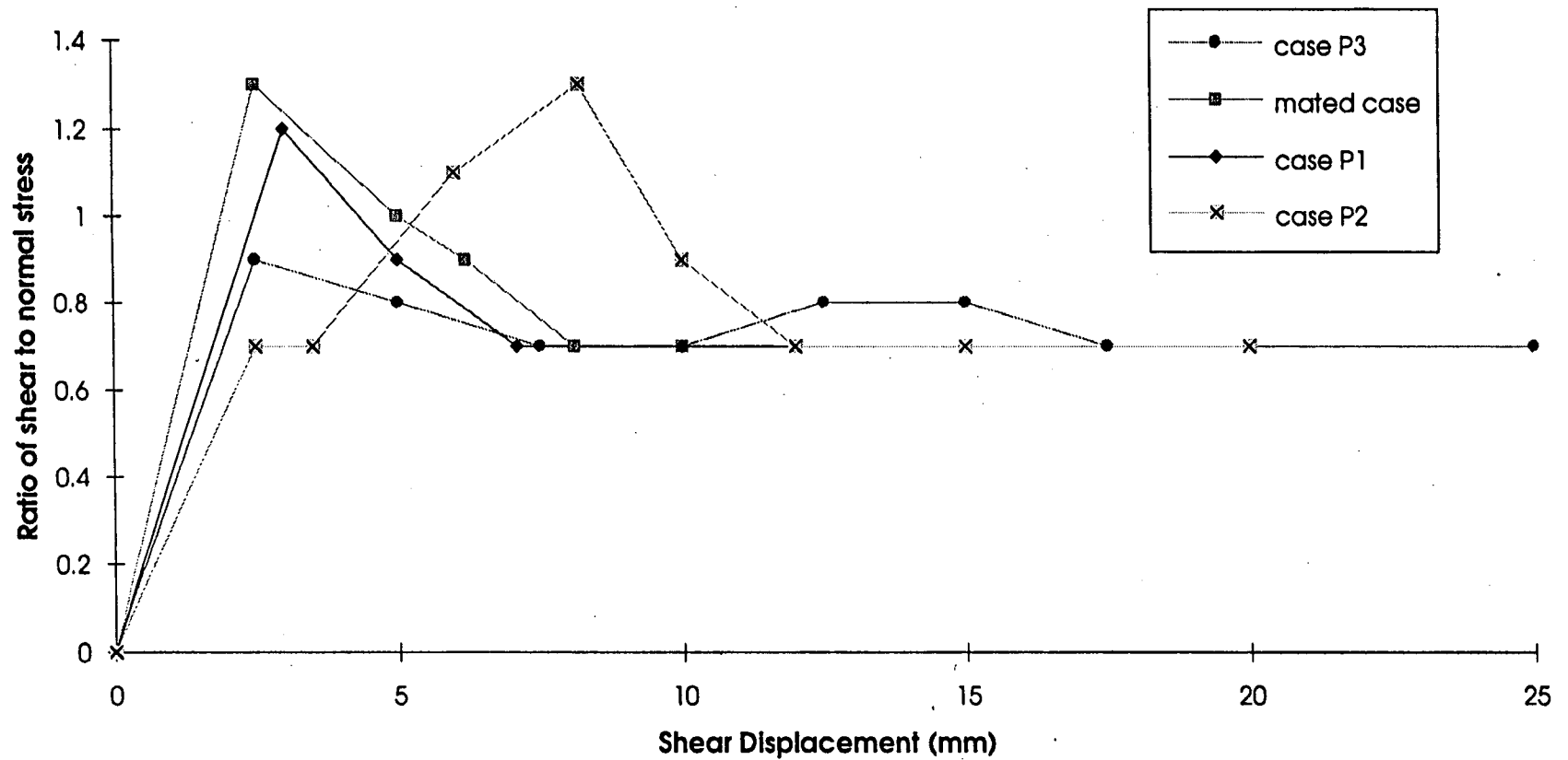
$$(y_i)_{u+\Delta u} = (y_i)_u + \Delta u * \tan i(u) \quad \forall \quad i=1..n \quad (5.7)$$

where  $(x_i, y_i)$  is point  $i$  of the upper profile and  $n$  is the total number of upper profile points.

- (4) Repeat steps 1-3 up to the desired displacement distance. The value of  $i(\Delta u)$  used at each increment is stored for calculating the dilatancy curve using Eqn. (5.4) and the shear stress-shear deformation curve using Eqn. (5.5).
- (5) If the aperture becomes greater than zero everywhere along the opposing profiles during any displacement increment, the upper profile is lowered parallel to the mean joint plane until atleast one point has an aperture of zero. This adjustment is realistic as the normal stress will almost always be large enough to make this happen in reality.

This new procedure was coded in a program. The procedure described above was modified slightly to minimize interpenetration errors caused by discretizing the analysis. Figure 5.5 shows a discrete representation of opposing profiles. The upper profile will dilate along the dilatancy path between lower profile points 4 and 5 during right lateral shearing as shown in Figure 5.5. All upper profile points follow this dilatancy path including the upper profile point 3. If the dilatancy path is followed over the entire increment of  $\Delta u$  by upper profile point 3, that point will cause an interpenetration error at the end of the  $\Delta u$  increment by intersecting the lower block below the location of lower profile point

**Figure 5.4: Comparison of shear stress-shear deformation curves for mated and unmated opposing profiles**





4 as shown in the figure. This interpenetration error is purely the consequence of discretizing the upper and lower joint walls into points separated by  $\Delta u$ . To avoid this error, the dilatancy path can be followed from point 3 up to point 'a' and then the path can be switched to the interpolated profile between lower profile points 3 and 4. Also, the discretization error can be reduced, and may be avoided altogether, by decreasing the size of the  $\Delta u$  increment. For instance, in Figure 5.5, if  $\Delta u$  were reduced to the distance between lower profile points 3 and 'a', there would be no interpenetration by upper profile point 3, if the finer lower profile followed the interpolation between lower profile points 3 and 4 shown in Figure 5.5.

The discretization error can be detected during any displacement increment by finding the distance to the intersection point ('a' in Figure 5.5) from where the interpenetration error starts to accumulate:

$$u_i = \frac{a_i}{m_{lp} - \tan i(\Delta u)} \quad (5.8)$$

where  $u_i$  is the displacement distance from point  $i$  at which the interpenetration error begins to accumulate ( $u_i \leq \Delta u$ ),  $a_i$  is the aperture at point  $i$ , and  $m_{lp}$  is the interpolated slope between point  $i$  and  $i+1$ .

If  $u_i \geq \Delta u$  between any pair of consecutive points, the algorithm follows the procedure described previously. However, if an interpenetration error is detected (i.e. if  $u_i < \Delta u$  between any pair of consecutive points), the algorithm makes a correction to the usual procedure by using  $m_{lp}$  between  $u_i$  and  $\Delta u$  instead of  $i(\Delta u)$ . This correction is made using the  $m_{lp}$  corresponding to the smallest value of  $u_i$ , if more than one pair of consecutive profile points cause an interpenetration error during any increment of displacement.

The algorithm was tested using opposing profiles consisting of the lower profile of Figure 5.1 and the upper profile  $P_2$  shown in Figure 5.3. These profiles were discretized using a sampling interval of 1 mm. Figure 5.6 shows the dilatancy curves computed using the algorithm and using a hand simulation of the shear displacement behavior. Figure 5.6 shows that the algorithm produces results which are very close to those from the physical simulation of dilatancy. Unlike the dilatancy curve obtained using Schneider's method, shown in Figure 5.2, the new algorithm described here captures the initial contractile behavior of this joint. The small discrepancies between the two curves are most likely due to the linear interpolations used in the new algorithm when correcting for discretization errors.

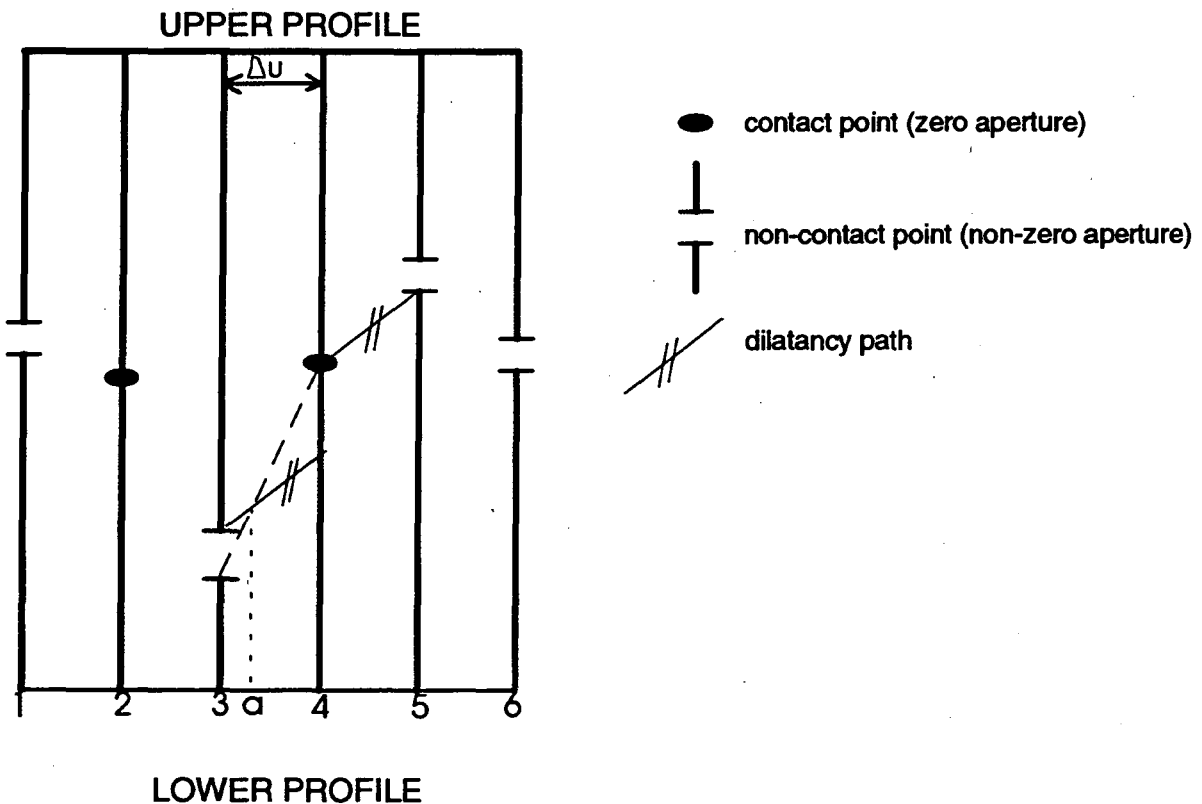


Figure 5.5: Discrete representation of opposing profiles

### 5.1.3 Application to borehole 3-5 joint 13-1

The program using the new algorithm described in the last section was applied to the unrolled opposing profiles obtained using the method described in Section 4.4.2 for joint 13-1 of borehole 3-5. Figure 5.7 shows the dilatancy curve and Figure 5.8 shows the shear stress-shear deformation curve produced by the program for a displacement distance of 23 mm. The dilatancy curve in Figure 5.7 has the characteristic concave shape with the rate of dilatancy decreasing as shear displacement proceeds. The shear stress-shear deformation curve of Figure 5.8 shows the ratio of shear stress to normal stress to be within a reasonable value of 1.4. The multiple peaks shown in Figure 5.8 are the result of the upper profile being dropped to meet the lower profile each time the opposing profiles loose contact and because asperity shearing is not accounted for.

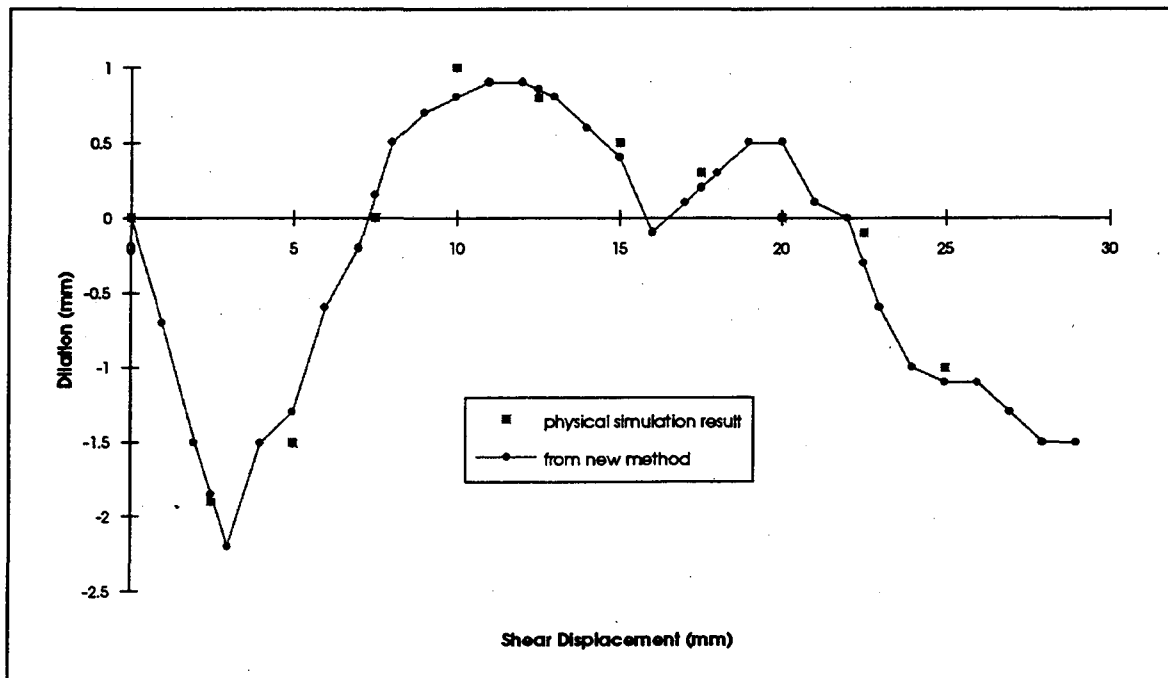


Figure 5.6: Comparison of dilatancy curves from new method and physical simulation

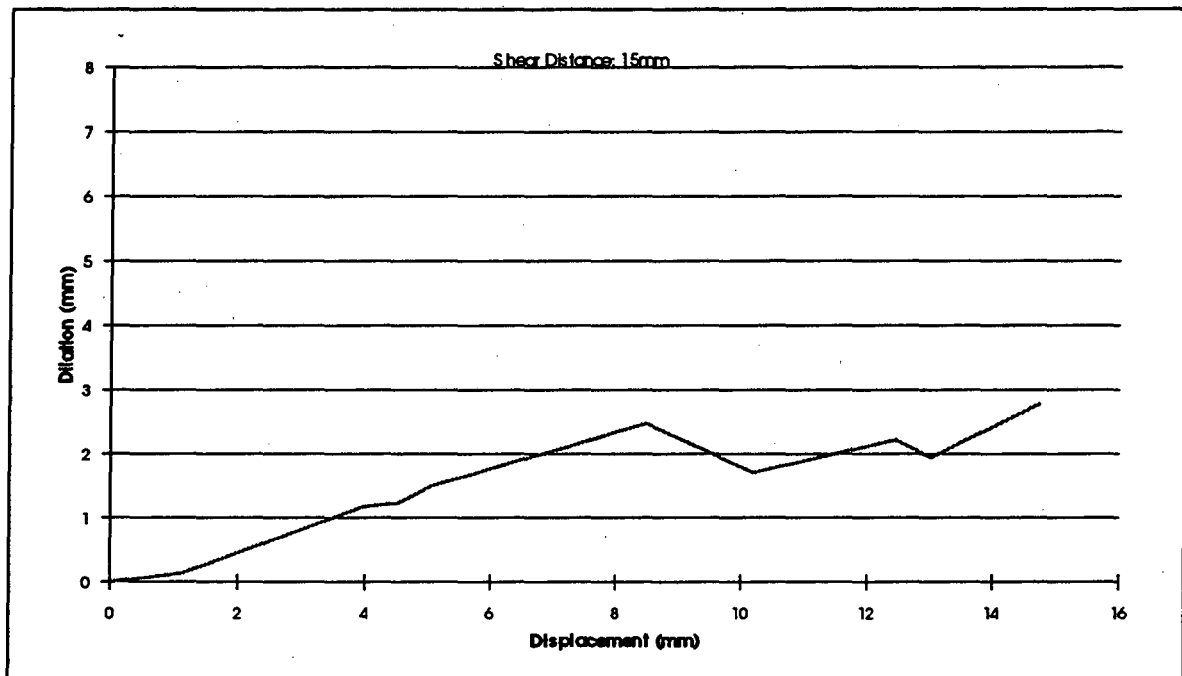


Figure 5.7: Dilatancy curve for joint 13-1 of borehole 3-5

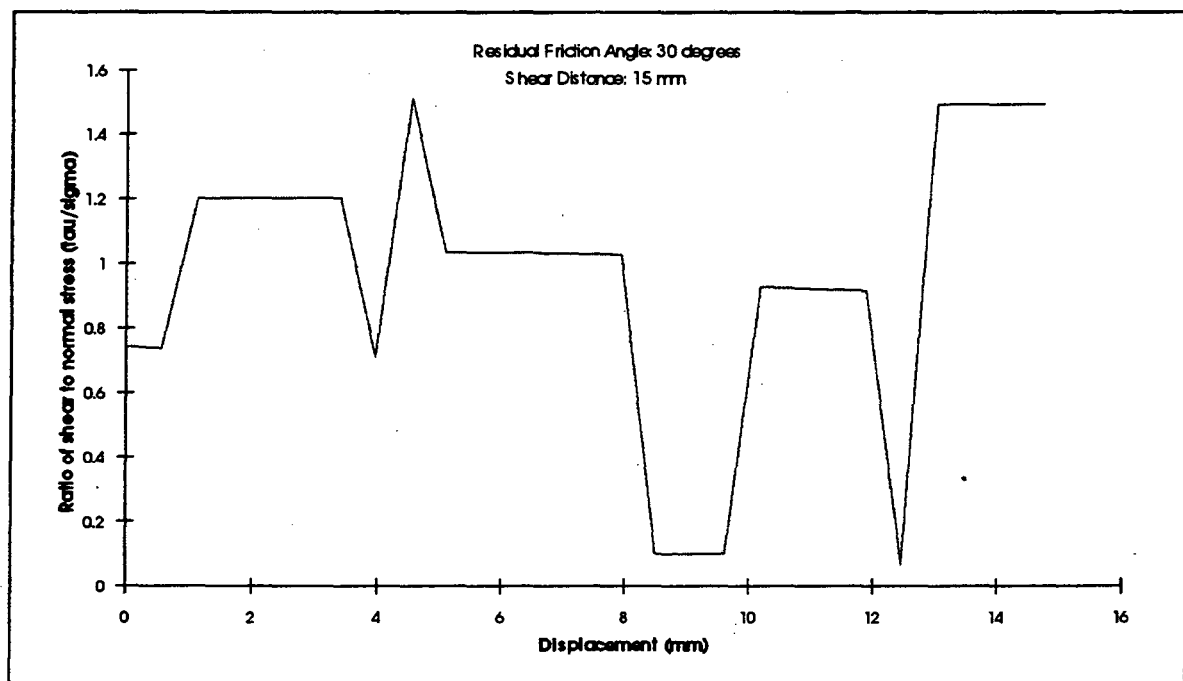


Figure 5.8: Shear stress-shear deformation curve for joint 13-1 of borehole 3-5

## 5.2 Numerical Simulation of a Direct Shear Test using Discontinuous Deformation Analysis

The kinematic shear deformation analysis described in the previous section cannot account for the mechanical interaction of the opposing profiles and shear displacement rate. This section describes a way to overcome these limitations of the kinematic analysis using Discontinuous Deformation Analysis (DDA).

### 5.2.1 Background on DDA

DDA is a numerical analysis for simulating the statics and dynamics of a two-dimensional rock block systems developed by Shi(1985). The displacement of a point  $(x, y)$  within a block are given by:

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} 1 & 0 & -(y-y_o) & (x-x_o) & 0 & (y-y_o)/2 \\ 0 & 1 & (x-x_o) & 0 & (y-y_o) & (x-x_o)/2 \end{pmatrix} \begin{pmatrix} u_o \\ v_o \\ r_o \\ \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} \quad (5.9)$$

where  $(u, v)$  is the total displacement of point  $(x, y)$ ,  $(x_o, y_o)$  is the block centroid,  $(u_o, v_o)$  is the displacement of the centroid,  $r_o$  is the rotation about  $(x_o, y_o)$ , and  $\varepsilon_x, \varepsilon_y, \gamma_{xy}$  are the normal and shear strains of the block.

Equilibrium equations of a system of blocks are found by minimizing the total potential energy,  $\Pi$

$$\frac{\partial \Pi}{\partial d_{ri}} = 0, \quad r = 1, \dots, 6 \quad (5.10)$$

where  $d_{ri}$  is the deformation variable for block  $i$ .

The resulting system of equations have the form

$$\begin{pmatrix} K_{11} & K_{12} & K_{13} & \dots & K_{1n} \\ K_{21} & K_{22} & K_{23} & \dots & K_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ K_{n1} & K_{n2} & K_{n3} & \dots & K_{nn} \end{pmatrix} \begin{pmatrix} D_1 \\ D_2 \\ \cdot \\ \cdot \\ D_n \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ \cdot \\ \cdot \\ F_n \end{pmatrix} \quad (5.11)$$

Displacements and strains during each time step are found by solving the system  $\mathbf{KD}=\mathbf{F}$ . The FORTRAN version of DDA used here was developed by Ke (1993). The DDA formulation assumes the strains within each block are constant.

### 5.2.2 Description of the DDA direct shear test configuration

The unrolled opposing BSS profiles were used in a DDA direct shear simulation as shown in Figure 5.9. A block was attached to each opposing profile and the shear stress was measured at a point on the left side of the upper block. The direct shear simulation was displacement controlled, i.e. increments of displacement were prescribed and the resulting shear stress computed. The upper and lower blocks were given very high values of Young's modulus to prevent elastic deformations of the blocks from causing higher shear stress values than predicted by limit equilibrium analysis for rigid blocks. The lower block was constrained by a roller and two fixed points as shown in Figure 5.9. A constant normal load was applied at the center of the upper block during the simulated test.

The DDA shear test was performed on a test case consisting of a perfectly mated saw-tooth profile as shown in Figure 5.10. A normal load of 1000 kN was applied at the center of the upper block (point 6). The lower block was constrained by fixed points 1 and 2 and a roller just below point 4. The

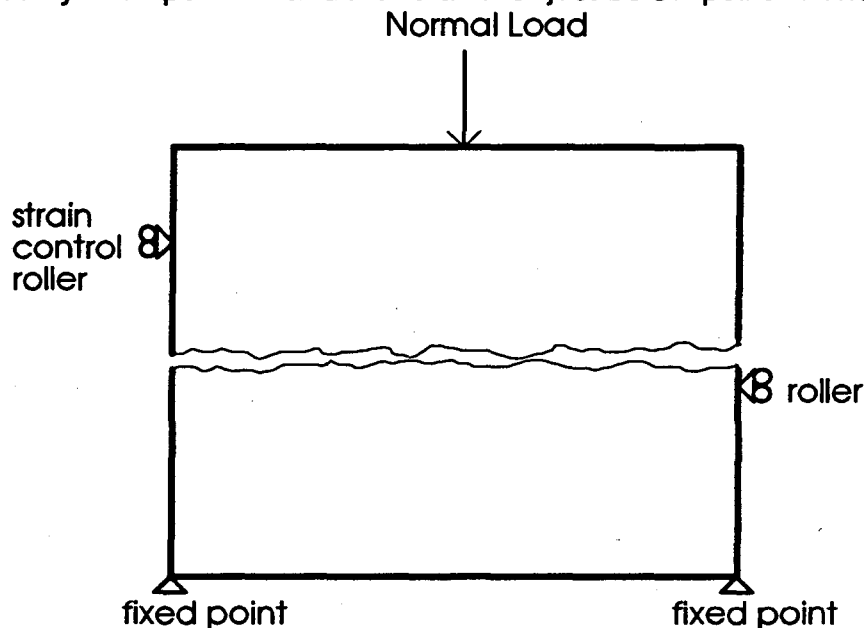


Figure 5.9: Configuration of DDA direct shear test

displacement of the upper block was measured by monitoring point 7 while the shear force was measured from the spring at point 3. The DDA result for this configuration was compared to limit equilibrium predictions based on Eqn. 4.1 as shown in Figure 5.11. The DDA result agrees with the limit equilibrium prediction except at a displacement of about 0.10 m. Here DDA's prediction of the shear force overshoots the limit equilibrium value, but soon drops down to the limit equilibrium value.

The DDA simulation was also performed assuming properties of joint 13-1 from borehole 3-5 and two additional joints from borehole 4-1. As reported in Table 4.1, the roughness of joint 13-1 is close to isotropic at small scales. Thus, the roughness profile of joint 13-1 may be unrolled to obtain a representative two

dimensional sample of the surface roughness. Table 5.1 shows the results of anisotropy analysis performed on the two joints 48-1 and 64-1 from borehole 4-1 used in the DDA direct shear simulation. Joints 48-1 and 64-1 can be expected to provide representative two dimensional surface roughness samples for the direct shear test simulation.

**Table 5.1: Anisotropy of joints in borehole 4-1**

| Joint                                              | Lower Profile Scales in mm |    |    | Upper Profile Scales in mm |    |    |
|----------------------------------------------------|----------------------------|----|----|----------------------------|----|----|
| Label                                              | 2                          | 8  | 14 | 2                          | 8  | 14 |
| 48-1                                               | I                          | NI | NI | I                          | NI | NI |
| 64-1                                               | I                          | NI | NI | I                          | NI | NI |
| A: anisotropic; I: isotropic; NI: nearly isotropic |                            |    |    |                            |    |    |

### 5.2.3 Test results and comparison to laboratory measurements

The configuration of the DDA direct shear test for joint 13-1 is shown in Figure 5.12. Only the unrolled profile of joint 13-1 from 150 mm to 396 mm was used in the test to avoid the high aperture measurement error segment as described in Section 3.4.2. A normal load of 1475 kN was applied at the center of the upper block. Figure 5.13 and 3.28 show the test results. Also shown in these figures are the results from laboratory direct shear testing of joint 13-1 in a core sample and results from the kinematic analysis described in Section 3.5. All three dilatancy curves in Figure 5.13 are close up to a shear displacement of about 2 mm. After that, the dilatancy curves from DDA and the kinematic analysis remain close to each other up to a displacement of 3.9 mm, but together diverge from the laboratory curve. This divergence is due to crushing of the asperities in the laboratory test. Neither DDA nor the kinematic analysis take asperity crushing into account and thus overestimate the dilatancy. As displacement proceeds, the kinematic analysis curve predicts a nearly constant



# LEGEND

Block boundary

— : real joints

----- : gen. joints

1 Block number

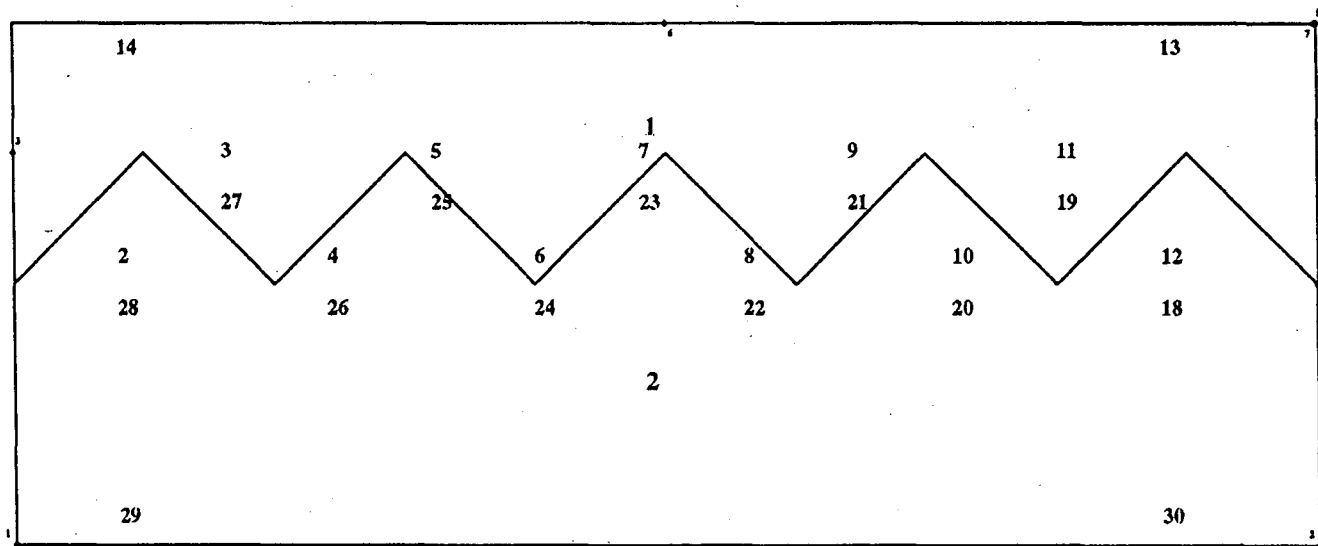
2 Vertex number

Point -

• : fixed, loading

• : fixed, unloading

----- Bolting lines



## SCALE

Length  
0.2E-01

Figure 5.10: Configuration of DDA shear test case

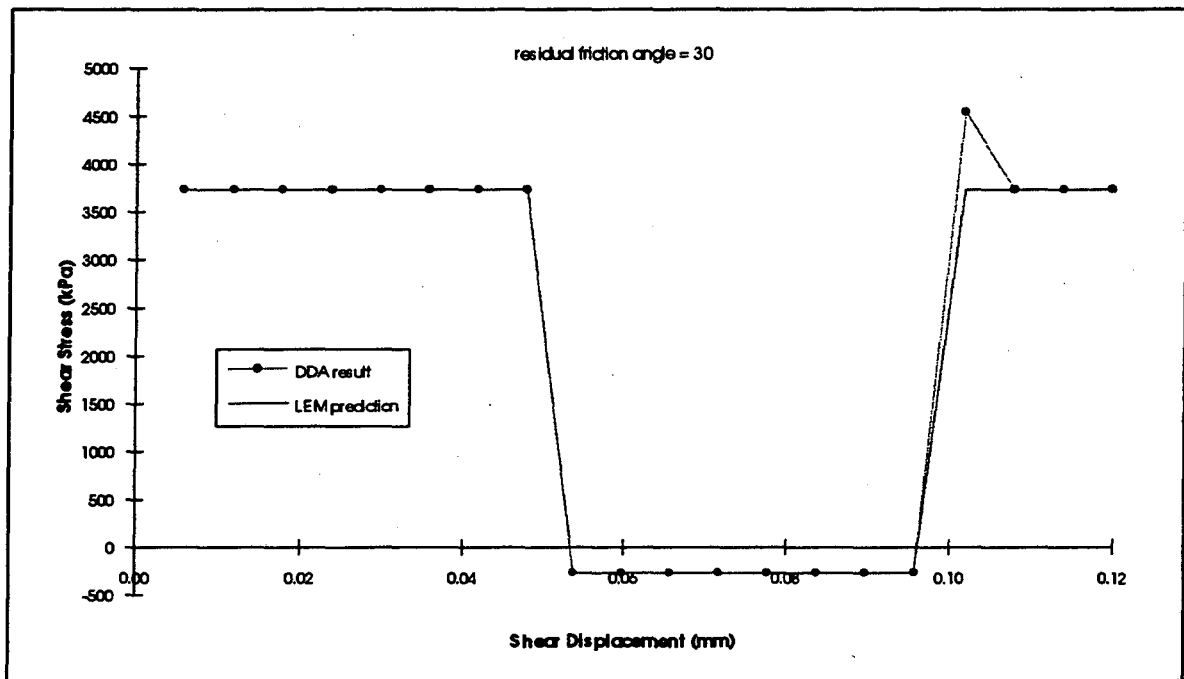


Figure 5.11: Results from DDA and Limit Equilibrium for test case

positive increment of dilation over that predicted by the DDA curve. This is because unlike DDA, the kinematic analysis does not take elastic deformations of the upper block and joint into account. The shapes of the DDA and kinematic analysis dilatancy curves are similar, but not identical. The similarity arises from the same peak dilation angles used at each increment of displacement in both methods. The discrepancy is due to the fact that the velocity acquired by the upper block in the DDA test may cause the upper joint profile to skip over parts of the lower profile. This skipping phenomena does not happen in the kinematic analysis. Figure 5.14 shows a comparison of the shear stresses from the three methods. The peak stress from the DDA simulation is close to but lower than the laboratory result. The residual shear stress values from DDA are a bit higher than the laboratory values. Around a displacement of 4 mm, the DDA shear stress value shows a high fluctuation. This fluctuation is due to a collision when a point on the upper profile first makes contact with a new segment of the

# LEGEND

Block boundary

— : real joints

--- : gen. joints

1 Block number

Point -

• : fixed tapping

• : block measured

----- Bolting lines

## SCALE

Length

— 0.1E-01

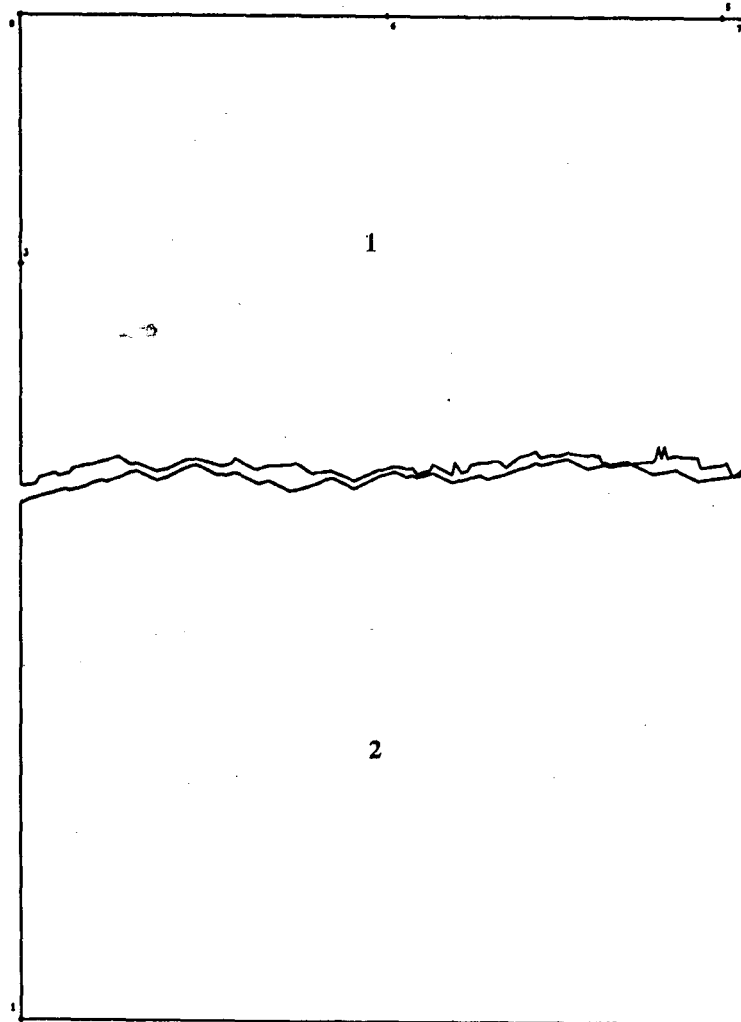


Figure 5.12: Direct shear test configuration for joint 13-1

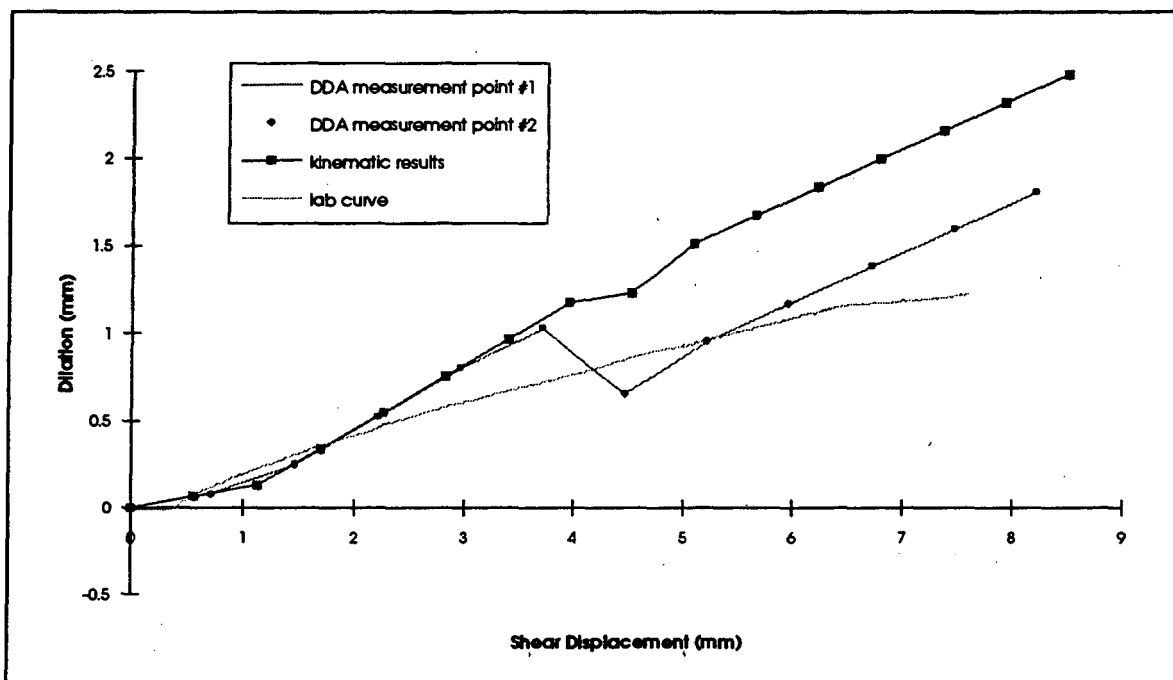


Figure 5.13: Dilatancy curves for joint 13-1

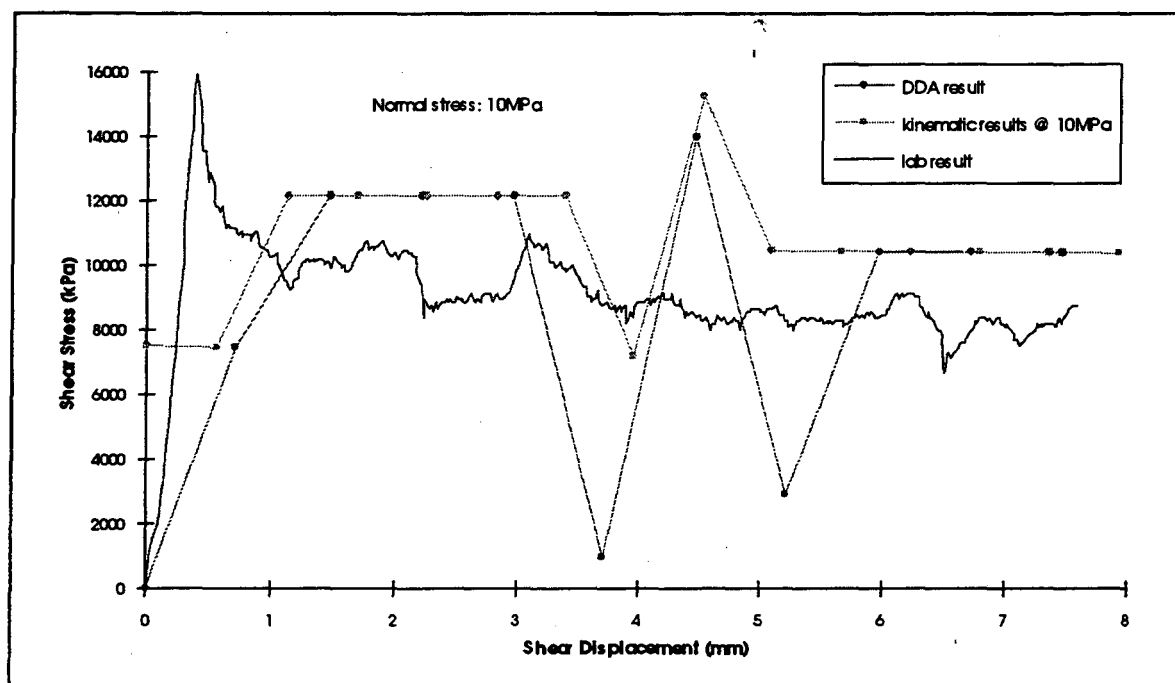


Figure 5.14: Shear stress-shear displacement curves for 13-1

lower profile. The collision causes a high shear stress values which reduces to the stable value as shown in the comparison of DDA and limit equilibrium results in Figure 5.11. The shear stress predicted by the kinematic analysis is very similar to the DDA result. The kinematic analysis prediction of shear stress also fluctuates at shear displacements of about 3.5 to 5 mm.

Figures 5.15 and 5.16 show comparisons of the DDA, kinematic analysis and laboratory results for joint 48-1. The tests on joint 48-1 were done at a much lower normal stress level (0.1 MPa) than joint 13-1. The lower normal stress level was expected to result in less asperity crushing in the laboratory test and thus give results closer to the DDA simulation values. However, Figure 5.15 shows the dilation predicted by DDA to be significantly higher than the measured laboratory values during the initial 5.5 mm of shear displacement. The discrepancy could be due to some surface roughness anisotropy, asperity crushing or both. The kinematic analysis dilatancy prediction is even higher than the DDA value, as expected, since the kinematic analysis does not take elastic deformation into account. The DDA and kinematic analysis predictions of shear strength are significantly lower than the laboratory measurement as shown in Figure 5.16. Unlike the clear peak strength seen in the laboratory test of joint 13-1, the low stress level used in the test results in a series of high shear stress values.

Figures 3.31 and 3.32 show the comparison of DDA, kinematic analysis and laboratory results for joint 64-1. As with joint 48-1, a low normal stress level was used in these tests (0.1 MPa). The dilatancy curves from DDA and the laboratory are fairly close up to a shear displacement of 4 mm while the kinematic analysis prediction is high, as expected. The shear stress predicted by DDA is again lower than the laboratory values. While the kinematic analysis shear stress prediction is closer to the laboratory measurement than the DDA

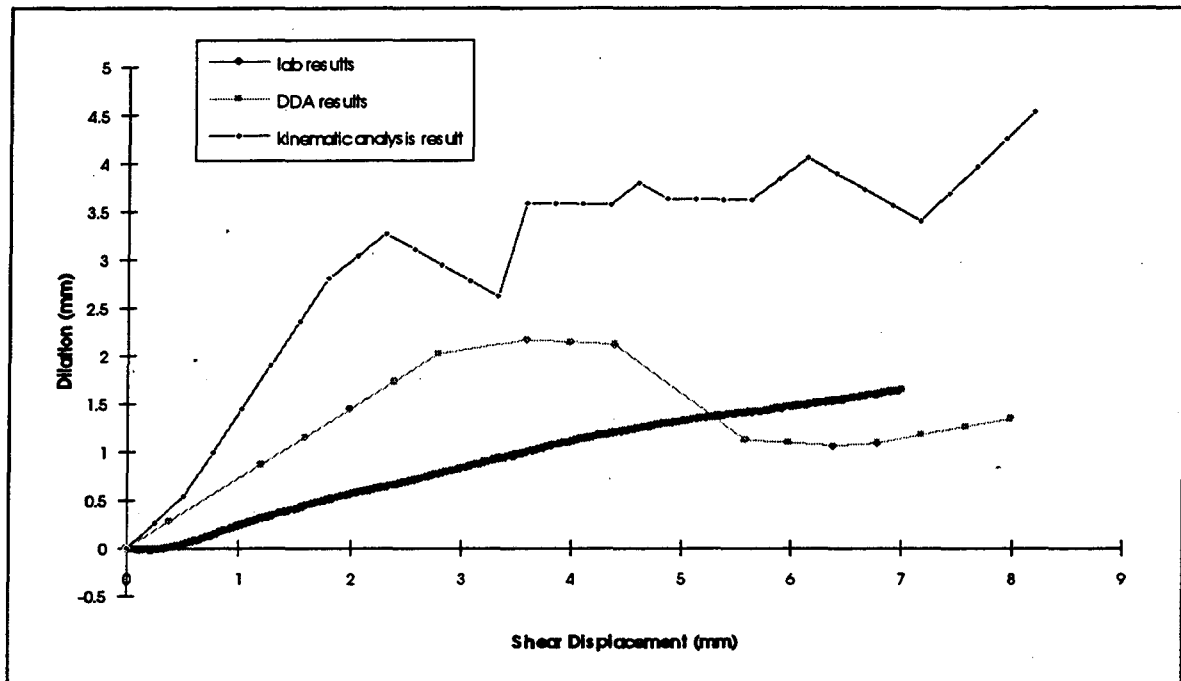


Figure 5.15: Dilation curves for joint 48-1

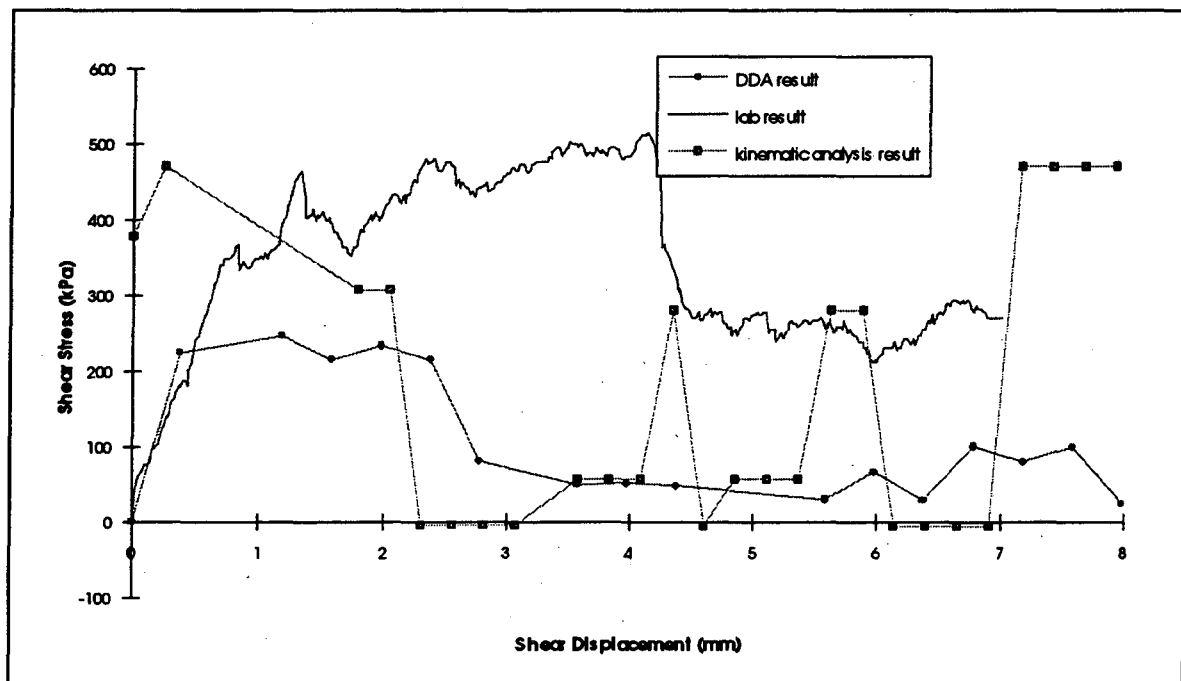


Figure 5.16: Shear stress-shear deformation curves for joint 48-1

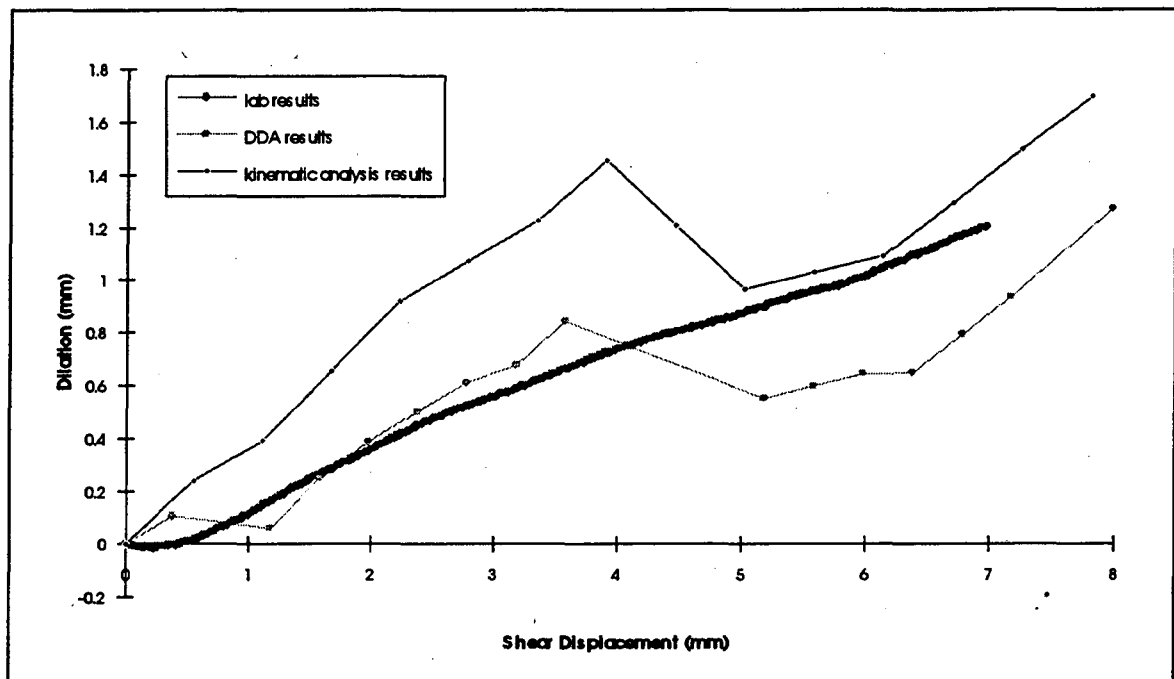


Figure 5.17: Dilation curves for joint 64-1

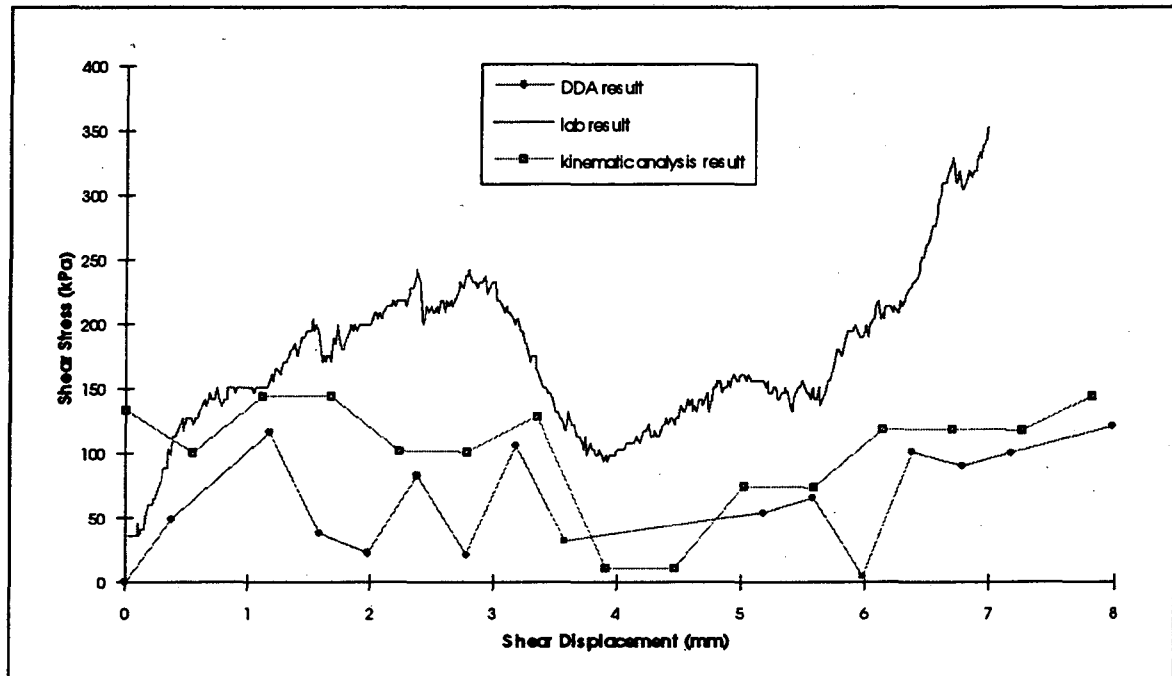


Figure 5.18: Shear stress-shear deformation curves for joint 64-1

results. Due to the low stress level, the laboratory curve in Figure 5.18 rises towards a second peak strength value, indicating little asperity crushing is being done during the shearing process.

Overall, the comparisons made here between the laboratory measurements, kinematic analysis and DDA simulations give mixed results. Results on joint 13-1 suggest BSS data can be analyzed for shear strength and dilatancy using the methods described here. The two joints in borehole 4-1 indicate the kinematic analysis and DDA simulation may underestimate the joint strength. One reason the kinematic analysis and DDA simulation did not work as well in the case of borehole 4-1 joints may be, that unlike the porphyritic granite of joint 13-1, the weaker rhyolite in the case of joints 48-1 and 64-1 may have led to more asperity crushing. If asperity crushing was extensive in the laboratory test, the kinematic analysis and DDA simulations can be expected to deviate from the lab result, as neither of the analysis take asperity crushing and subsequent influence of the broken asperities into account. More comparative studies in the future would lead to a better understanding of the conditions under which the shear strength analysis using the BSS data can provide reliable results.



## **CHAPTER 6**

### **CONCLUSIONS AND RECOMMENDATIONS**

Several new in-situ methods of joint characterization which can be performed using BSS data. Together, these methods provide a computer based approach for the assessment of in-situ joint strength and its spatial variability. Additionally, the methods developed in this thesis provide a starting point to pursue the development of various new methods of site characterization described in Section 2.3.2.

#### **6.1 Current Limitations**

The image processing method described in Chapter 3 to extract the joint roughness profile takes about one hour per joint to execute due to the need for extensive user interaction. This analysis rate needs to be improved to make it feasible to extract roughness profiles within the time and budget constraints of construction projects. In order to improve the extraction rate, the edge extraction method has to be automated as much as possible so that user interaction is minimized. Improvements in automation appear to be feasible using existing image processing methods.

The analysis of the roughness profile described in this thesis relies on the assumption that the orientation of the mean joint plane can be taken to be the orientation of a plane approximated by the BSS joint profile. Since the analysis results are sensitive to the value of the mean orientation used, any error in the mean orientation will result in errors in the analysis results. For instance, the assumption that the mean plane is equivalent to the BSS profile sample orientation could be wrong because of joint waviness. Averages over many joints from the same set should provide a more reliable mean orientation to use with the various analysis described in this thesis.

All of the joints seen in the BSS images were assumed to be real joints whose roughness profiles had not been altered during drilling. In fact, the drilling process may have created new fractures and changed the roughness profiles of some of the existing fractures. In some cases, a crystal separated by a joint shows the roughness profile to have been left unaltered by the drilling process. Portions of some joints show unusually sharp edges indicating recent fracturing during drilling. In general, it is difficult to judge if the drilling has significantly changed the natural condition.

## **6.2 Recommendations**

The current BSS probe should be improved to include a sufficient number of bands of reflectance measurement so that mineralogy identification becomes possible. This would enable the BSS data to be used to completely characterize joint strength and also enhance the feasibility of other new analyses such as the technique for determining if a joint has conducted fluids in the past based on joint wall mineralogy.

The BSS probe needs to be fitted with a centering device. Without a centering device, the probe will generally not stay centered if there is a deviation of the borehole from vertical. When the probe is not centered, the pixels in the BSS image will not represent equal areas on the borehole wall and the interpretation of the data will be in error.

More comparisons of DDA direct shear tests and laboratory tests need to be made to understand the conditions under which the DDA test of BSS data may provide reliable results. Only the part of the unrolled profile which approximately corresponds to the direction of laboratory shear testing may be used in the DDA simulation if the joint roughness is even slightly anisotropic. The DDA model may also be improved by including artificial joints (Ke, 1993) at the base of the asperities. This would enable the DDA model to simulate the upper

profile shearing through lower profile asperities (or visa versa) instead of being constrained to dilate or contract only.

## REFERENCES

- Bandis, S., Lumsden, A.C. and Barton, N. (1983) Fundamentals of rock joint deformation, *International Journal of Rock Mechanics and Mining Sciences*, Vol 20, pp. 249-268
- Bandis, S. (1994) Rock mass and site characterization, In Hudson, J. (ed.) *Comprehensive Rock Engineering*, Pergamon Press, New York, V.1, pp.155-183
- Barton, C. (1988) *Development of in-situ stress measurement techniques for deep drillholes*, PhD Thesis, Stanford University
- Barton, N. (1974) A review of the shear strength of filled discontinuities in rock, In *Proc. Bergmekanikk*, Oslo, Norway, pp. 19.1-19.38, Tapir, Oslo
- Barton, N. and Choubey, V. (1977) The shear strength of rocks in theory and practice, *Rock Mechanics*, V.10, pp. 1-54
- Barton, N.R. and Bandis, S.C. (1980) Some scale effects on the shear strength of joints, *International Journal of Rock Mechanics and Mining Sciences*, Vol 17, pp. 69-73
- Barton, N., Bandis, S. and Bakhtar, K. (1985) Strength, deformation and conductivity coupling of rock joints, *International Journal of Rock Mechanics and Mining Sciences*, Vol 22, pp. 121-140
- Bieniawski, Z.T. (1989) *Engineering rock mass classifications*, Wiley, New York
- Borchers, J.W., Morin, R.H. and Hickman, S. (1993) Characterization of fractures in granitic rocks at Wawona, Yosemite National Park, California, *Trans. 1993 Fall Meeting*, American Geophysical Union, San Francisco
- Boyle, W.J. (1986) *The influence of initial stresses on the movement of rock blocks around underground openings*, PhD Thesis, University of California at Berkeley

- Brekke, T.L. and Howard, T.R. (1973) *Functional classification of gouge materials from seams and faults in relation to stability problems in underground openings*, Geotechnical Engineering Report, University of California, Berkeley
- Briggs, R.O. (1964), Development of a Downhole Television Camera, *Fifth Annual SPWLA Logging Symposium*, Midland, Texas, pp. 13-15
- Brown, S.R. and Scholz, C.H. (1985) Broad bandwidth study of the topography of natural joints, *Journal of Geophysical Research*, 90,12, pp.575-12,582
- Brown, S.R., Kranz, R.L., and Bonner, B.P. (1986) Correlation between the surfaces of natural rock joints, *Geophysical Research Letters*, V.13, No. 12, pp. 1430-1433
- Cluff, L.S. (1966), *Borehole Cameras*, Report to the American Society for Testing and Materials, Committee D-18, Section E, Subcommittee 1
- Cook, N.G.W. (1992), Natural joints in rocks, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 29, pp.198-223
- Dershowitz, W.S. and Einstein, H.H. (1988) Characterizing rock joint geometry with joint system models, *Rock Mechanics and Rock Engineering*, V.21, No.1, pp.21-52
- Fabbri, A.G. (1984) *Image processing of geological data*, Van Nostrand Reinhold Co., New York
- Einstein, H. (1993) Modern developments in discontinuity analysis - the persistence-connectivity problem. In Hudson, J. (ed.) *Comprehensive Rock Engineering*, Pergamon Press, New York, V.3, pp.193-213
- Fecker, E. and Rengers, N. (1971) Measurement of large scale roughness of rock planes by means of profilograph and geologic compass, *Proceedings, International Symposium on Rock Fracture*, Nancy (ISRM), paper 1-18
- Goodman, R.E. (1976), *Methods of Geological Engineering in Discontinuous Rocks*, West Publishing Co., St. Paul

- Goodman, R.E. and Shi, G.H (1985), *Block Theory and its Application to Rock Engineering*, Prentice-Hall, Inc. Englewood Cliffs, New Jersey
- Gonzalez, R.C. and Woods, R.E. (1992) *Digital Image Processing*, Addison Wesley, New York
- Harrison, J.P. and Goodfellow, R.J.F. (1993) Effect of scale on roughness anisotropy and magnitude, In *Scale effects in rock masses*, Cunha, A.P. (ed), Balkema
- Hatzor, Y. (1992), *Validation of Block Theory Using Field Case Histories*, Ph.D. Thesis, University of California at Berkeley
- Heuze, F.E. (1979) Dilatant effects of rock joints, *Proc. Fourth Congress International Society of Rock Mechanics*, Montreux, Balkema, Rotterdam, pp.169-175
- Huang, T.H. and Doong, Y.S. (1990) Anisotropic shear strength of rock joints, *Proc. International Symposium on Rock Joints*, Loen, Norway, Balkema, Rotterdam
- Hudson, J.A. (1994) Rock properties, testing methods and site characterization, In Hudson, J. (ed.) *Comprehensive Rock Engineering*, Pergamon Press, New York, V.3, pp.1-40
- Ladanyi, B. and Archambault, G. (1970) Simulation of shear behavior of a jointed rockmass, In *Proc. 11th U.S. Symp. Rock Mech.*, Berkeley, CA (Edited by W.H. Somerton), pp. 105-125
- Lee, J.W. (1982), *Well Testing*, Society of Petroleum Engineers of AIME, New York
- Long, J.C.S (1994) Construction of equivalent discontinuum models for fracture hydrology, In Hudson, J. (ed.) *Comprehensive Rock Engineering*, Pergamon Press, New York, V.3, pp.241-296

- Makurat, A., Barton, N., Rad, N.S. and Bandis, S.C. (1990) Joint conductivity variation due to normal and shear deformation. In *Proc. Int. Conf. Rock Joints*, Loen, Norway (edited by N. Barton and O. Stephansson), pp. 534-540
- Patton, F.D. (1966) Multiple modes of shear failure in rock, *Proc. 1st Cong. ISRM* (Lisbon), Vol. 1, pp.509-513
- Pointe, P.R. La (1994) Pattern analysis and simulation of joints in rock engineering, In Hudson, J. (ed.) *Comprehensive Rock Engineering*, Pergamon Press, New York, V.3, pp.215-240
- Priest, S.D. and Hudson, J.A. (1976) Discontinuity spacings in rock, *International Journal of Rock Mechanics and Mining Sciences*, Vol 13, pp. 135-148
- Ramsay, J.G. and Huber, M.I. (1983) *The techniques of modern structural geology, volume 1: strain analysis*, Academic Press, San Diego
- Rengers, N. (1970) Influence of surface roughness on the friction properties of rock planes, *Proc. 2nd Congress ISRM (Belgrade)*, V.1, pp. 229-234
- Schneider, H.J. (1976) Comments in *Proceedings of International Symposium on Numerical Methods in Soil Mechanics and Rock Mechanics*, G. Borm and H. Meissner, Eds., pp. 220-223 (Inst. fur Bodenmechanik und Felsmechanik of Karlsruhe University, D-7500, Karlsruhe 1, Germany)
- Schneider, H.J. (1976) The friction and deformation behavior of rock joints, *Rock Mechanics and Rock Engineering*, V.8, No.3, pp.169-184
- Selby, M.J. (1982), *Hillslope Materials and Processes*, Oxford University Press, New York
- Shi, G.H. (1985) *Discontinuous deformation analysis: a new approach to the statics and dynamics of block systems*, PhD Thesis, University of California at Berkeley

- Shi, G.H. and Goodman, R.E. (1989), *The key blocks of unrolled joint traces in developed maps of tunnel walls*, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 13, pp.131-158
- Snow, D.T. (1970) The frequency and apertures of fractures in rocks, *International Journal of Rock Mechanics and Mining Sciences*, Vol. 7, pp.23-40
- Suppe, J. (1985), *Principles of Structural Geology*, Prentice-Hall, Inc. Englewood Cliffs, New Jersey
- Tang, W., Quek, S.T. (1986) Statistical model of boulder size and fraction, *Journal of Geotechnical Engineering*, ASCE, V. 112, No. 1, pp.79-90
- Tanimoto, C., Murai, S., Matsumoto, T., Kishida, K. and Ando, T. (1992) Immediate Image and its Analysis of Fractured and Jointed Rock Mass through the Borehole Scanner in *Proceedings of Fractured and Jointed Rock Masses*, Lake Tahoe, California
- Tanimoto, C., Kishida, K., Yoshizu, Y. and Kunii, K. (1994) Siesmic attenuation geotomographic technique in designing a large underground cavern, *Proc. ISRM Symposium*, Santiago, Chile
- Telford, W.M., Geldart, L.P. and Sheriff, R.E. (1990), *Applied Geophysics*, Cambridge University Press, Cambridge
- Thapa, B.B. and Goodman, R.E. (1994), The Induced Wedge Test, *International Journal of Rock Mechanics and Mining Sciences*
- Trantina, J.A. and Cluff, L.S. (1963), *NX Bore-Hole Camera*, American Society for Testing and Materials, Special Technical Publication No. 351
- Zemanek, J., Glenn, E.E., Norton, L.J. and Caldwell, R.L. (1970), *Formation evaluation by inspection with the borehole televiewer*, *Geophysics*, Vol. 35, pp. 254-269



## APPENDIX

### A. Roughness profile points extracted from BSS image for joint 13-1

Table A.1: Roughness profile points of joint 13-1

| <----->  | Upper      | Profile    | <----->  | <----->  | Lower      | Profile    | <----->  |
|----------|------------|------------|----------|----------|------------|------------|----------|
| rotation | depth data | azimuth    | depth    | rotation | depth data | azimuth    | depth    |
| data     | in image y | in degrees | in mm    | data     | in image y | in degrees | in mm    |
| 1        | 650        | 180.720001 | 13428.25 | 1        | 655        | 180.720001 | 13434.5  |
| 2        | 650        | 181.440002 | 13428.25 | 2        | 655        | 181.440002 | 13434.5  |
| 3        | 650        | 182.160004 | 13428.25 | 3        | 656        | 182.160004 | 13432.25 |
| 4        | 650        | 182.880005 | 13428.25 | 4        | 656        | 182.880005 | 13432.25 |
| 4        | 651        | 182.880005 | 13430.25 | 4        | 655        | 182.880005 | 13434.5  |
| 5        | 651        | 183.600006 | 13430.25 | 5        | 655        | 183.600006 | 13434.5  |
| 6        | 651        | 184.320007 | 13430.25 | 6        | 655        | 184.320007 | 13434.5  |
| 7        | 651        | 185.039993 | 13430.25 | 7        | 655        | 185.039993 | 13434.5  |
| 7        | 652        | 185.039993 | 13430.75 | 8        | 655        | 185.759995 | 13434.5  |
| 8        | 652        | 185.759995 | 13430.75 | 9        | 655        | 186.479996 | 13434.5  |
| 8        | 653        | 185.759995 | 13433    | 10       | 655        | 187.199997 | 13434.5  |
| 9        | 653        | 186.479996 | 13433    | 11       | 656        | 187.919998 | 13432.25 |
| 10       | 653        | 187.199997 | 13433    | 12       | 656        | 188.639999 | 13432.25 |
| 11       | 653        | 187.919998 | 13433    | 13       | 657        | 189.360001 | 13434.5  |
| 11       | 654        | 187.919998 | 13432.25 | 14       | 657        | 190.080002 | 13434.5  |
| 12       | 654        | 188.639999 | 13432.25 | 15       | 657        | 190.800003 | 13434.5  |
| 13       | 654        | 189.360001 | 13432.25 | 16       | 658        | 191.520004 | 13433.5  |
| 13       | 655        | 189.360001 | 13434.5  | 17       | 659        | 192.240005 | 13434    |
| 14       | 655        | 190.080002 | 13434.5  | 18       | 660        | 192.960007 | 13436    |
| 14       | 656        | 190.080002 | 13432.25 | 18       | 661        | 192.960007 | 13436.75 |
| 15       | 656        | 190.800003 | 13432.25 | 19       | 662        | 193.679993 | 13436    |
| 16       | 656        | 191.520004 | 13432.25 | 20       | 663        | 194.399994 | 13435.25 |
| 17       | 656        | 192.240005 | 13432.25 | 21       | 664        | 195.119995 | 13435.75 |
| 17       | 657        | 192.240005 | 13434.5  | 22       | 664        | 195.839996 | 13435.75 |
| 18       | 657        | 192.960007 | 13434.5  | 23       | 664        | 196.559998 | 13435.75 |
| 19       | 657        | 193.679993 | 13434.5  | 24       | 664        | 197.279999 | 13435.75 |
| 20       | 657        | 194.399994 | 13434.5  | 25       | 664        | 198        | 13435.75 |
| 21       | 657        | 195.119995 | 13434.5  | 25       | 663        | 198        | 13435.25 |
| 21       | 658        | 195.119995 | 13433.5  | 26       | 663        | 198.720001 | 13435.25 |
| 22       | 658        | 195.839996 | 13433.5  | 27       | 663        | 199.440002 | 13435.25 |
| 23       | 658        | 196.559998 | 13433.5  | 28       | 663        | 200.160004 | 13435.25 |
| 23       | 659        | 196.559998 | 13434    | 29       | 663        | 200.880005 | 13435.25 |
| 24       | 659        | 197.279999 | 13434    | 29       | 662        | 200.880005 | 13436    |
| 25       | 659        | 198        | 13434    | 30       | 662        | 201.600006 | 13436    |
| 26       | 659        | 198.720001 | 13434    | 31       | 662        | 202.320007 | 13436    |
| 27       | 659        | 199.440002 | 13434    | 32       | 662        | 203.039993 | 13436    |
| 28       | 659        | 200.160004 | 13434    | 33       | 662        | 203.759995 | 13436    |
| 29       | 659        | 200.880005 | 13434    | 34       | 662        | 204.479996 | 13436    |
| 30       | 659        | 201.600006 | 13434    | 35       | 663        | 205.199997 | 13435.25 |
| 31       | 658        | 202.320007 | 13433.5  | 36       | 663        | 205.919998 | 13435.25 |

|    |     |            |          |    |     |            |          |
|----|-----|------------|----------|----|-----|------------|----------|
| 32 | 658 | 203.039993 | 13433.5  | 37 | 663 | 206.639999 | 13435.25 |
| 33 | 658 | 203.759995 | 13433.5  | 38 | 663 | 207.360001 | 13435.25 |
| 34 | 657 | 204.479996 | 13434.5  | 39 | 663 | 208.080002 | 13435.25 |
| 35 | 657 | 205.199997 | 13434.5  | 40 | 663 | 208.800003 | 13435.25 |
| 36 | 657 | 205.919998 | 13434.5  | 41 | 663 | 209.520004 | 13435.25 |
| 37 | 657 | 206.639999 | 13434.5  | 42 | 663 | 210.240005 | 13435.25 |
| 38 | 657 | 207.360001 | 13434.5  | 43 | 663 | 210.960007 | 13435.25 |
| 38 | 658 | 207.360001 | 13433.5  | 44 | 663 | 211.679993 | 13435.25 |
| 39 | 658 | 208.080002 | 13433.5  | 45 | 663 | 212.399994 | 13435.25 |
| 40 | 658 | 208.800003 | 13433.5  | 46 | 663 | 213.119995 | 13435.25 |
| 41 | 658 | 209.520004 | 13433.5  | 47 | 663 | 213.839996 | 13435.25 |
| 41 | 659 | 209.520004 | 13434    | 48 | 664 | 214.559998 | 13435.75 |
| 42 | 659 | 210.240005 | 13434    | 49 | 664 | 215.279999 | 13435.75 |
| 43 | 659 | 210.960007 | 13434    | 50 | 664 | 216        | 13435.75 |
| 44 | 659 | 211.679993 | 13434    | 51 | 664 | 216.720001 | 13435.75 |
| 44 | 660 | 211.679993 | 13436    | 52 | 664 | 217.440002 | 13435.75 |
| 45 | 660 | 212.399994 | 13436    | 53 | 664 | 218.160004 | 13435.75 |
| 46 | 659 | 213.119995 | 13434    | 54 | 664 | 218.880005 | 13435.75 |
| 47 | 659 | 213.839996 | 13434    | 55 | 664 | 219.600006 | 13435.75 |
| 47 | 660 | 213.839996 | 13436    | 56 | 664 | 220.320007 | 13435.75 |
| 48 | 660 | 214.559998 | 13436    | 57 | 664 | 221.039993 | 13435.75 |
| 49 | 660 | 215.279999 | 13436    | 58 | 664 | 221.759995 | 13435.75 |
| 50 | 660 | 216        | 13436    | 59 | 664 | 222.479996 | 13435.75 |
| 51 | 660 | 216.720001 | 13436    | 60 | 664 | 223.199997 | 13435.75 |
| 51 | 661 | 216.720001 | 13436.75 | 61 | 664 | 223.919998 | 13435.75 |
| 52 | 661 | 217.440002 | 13436.75 | 62 | 664 | 224.639999 | 13435.75 |
| 53 | 661 | 218.160004 | 13436.75 | 63 | 664 | 225.360001 | 13435.75 |
| 54 | 661 | 218.880005 | 13436.75 | 64 | 665 | 226.080002 | 13437.75 |
| 55 | 661 | 219.600006 | 13436.75 | 65 | 666 | 226.800003 | 13438.25 |
| 56 | 661 | 220.320007 | 13436.75 | 66 | 667 | 227.520004 | 13440.5  |
| 57 | 661 | 221.039993 | 13436.75 | 67 | 667 | 228.240005 | 13440.5  |
| 58 | 661 | 221.759995 | 13436.75 | 68 | 668 | 228.960007 | 13442.75 |
| 58 | 662 | 221.759995 | 13436    | 69 | 668 | 229.679993 | 13442.75 |
| 59 | 662 | 222.479996 | 13436    | 70 | 669 | 230.399994 | 13442    |
| 60 | 662 | 223.199997 | 13436    | 71 | 669 | 231.119995 | 13442    |
| 61 | 661 | 223.919998 | 13436.75 | 72 | 669 | 231.839996 | 13442    |
| 62 | 661 | 224.639999 | 13436.75 | 73 | 670 | 232.559998 | 13442.75 |
| 63 | 661 | 225.360001 | 13436.75 | 74 | 671 | 233.279999 | 13444.75 |
| 64 | 661 | 226.080002 | 13436.75 | 75 | 671 | 234        | 13444.75 |
| 64 | 662 | 226.080002 | 13436    | 76 | 671 | 234.720001 | 13444.75 |
| 65 | 662 | 226.800003 | 13436    | 77 | 671 | 235.440002 | 13444.75 |
| 66 | 662 | 227.520004 | 13436    | 78 | 671 | 236.160004 | 13444.75 |
| 67 | 662 | 228.240005 | 13436    | 79 | 671 | 236.880005 | 13444.75 |
| 68 | 662 | 228.960007 | 13436    | 79 | 670 | 236.880005 | 13442.75 |
| 69 | 662 | 229.679993 | 13436    | 80 | 670 | 237.600006 | 13442.75 |
| 70 | 662 | 230.399994 | 13436    | 81 | 670 | 238.320007 | 13442.75 |
| 71 | 662 | 231.119995 | 13436    | 82 | 670 | 239.039993 | 13442.75 |
| 71 | 663 | 231.119995 | 13435.25 | 82 | 669 | 239.039993 | 13442    |
| 72 | 663 | 231.839996 | 13435.25 | 83 | 669 | 239.759995 | 13442    |
| 73 | 663 | 232.559998 | 13435.25 | 84 | 669 | 240.479996 | 13442    |

|     |     |            |          |     |     |            |          |
|-----|-----|------------|----------|-----|-----|------------|----------|
| 73  | 664 | 232.559998 | 13435.75 | 85  | 669 | 241.199997 | 13442    |
| 74  | 664 | 233.279999 | 13435.75 | 86  | 669 | 241.919998 | 13442    |
| 75  | 664 | 234        | 13435.75 | 87  | 669 | 242.639999 | 13442    |
| 75  | 665 | 234        | 13437.75 | 88  | 669 | 243.360001 | 13442    |
| 76  | 665 | 234.720001 | 13437.75 | 89  | 669 | 244.080002 | 13442    |
| 77  | 665 | 235.440002 | 13437.75 | 90  | 669 | 244.800003 | 13442    |
| 78  | 665 | 236.160004 | 13437.75 | 91  | 669 | 245.520004 | 13442    |
| 79  | 665 | 236.880005 | 13437.75 | 92  | 669 | 246.240005 | 13442    |
| 80  | 665 | 237.600006 | 13437.75 | 93  | 669 | 246.960007 | 13442    |
| 81  | 665 | 238.320007 | 13437.75 | 94  | 669 | 247.679993 | 13442    |
| 82  | 665 | 239.039993 | 13437.75 | 95  | 669 | 248.399994 | 13442    |
| 83  | 664 | 239.759995 | 13435.75 | 95  | 668 | 248.399994 | 13442.75 |
| 84  | 664 | 240.479996 | 13435.75 | 96  | 668 | 249.119995 | 13442.75 |
| 85  | 664 | 241.199997 | 13435.75 | 97  | 668 | 249.839996 | 13442.75 |
| 86  | 664 | 241.919998 | 13435.75 | 98  | 668 | 250.559998 | 13442.75 |
| 87  | 664 | 242.639999 | 13435.75 | 99  | 668 | 251.279999 | 13442.75 |
| 88  | 664 | 243.360001 | 13435.75 | 100 | 668 | 252        | 13442.75 |
| 89  | 664 | 244.080002 | 13435.75 | 101 | 668 | 252.720001 | 13442.75 |
| 90  | 664 | 244.800003 | 13435.75 | 102 | 668 | 253.440002 | 13442.75 |
| 91  | 664 | 245.520004 | 13435.75 | 103 | 668 | 254.160004 | 13442.75 |
| 92  | 664 | 246.240005 | 13435.75 | 104 | 668 | 254.880005 | 13442.75 |
| 93  | 664 | 246.960007 | 13435.75 | 105 | 668 | 255.600006 | 13442.75 |
| 94  | 664 | 247.679993 | 13435.75 | 106 | 668 | 256.320007 | 13442.75 |
| 95  | 663 | 248.399994 | 13435.25 | 107 | 668 | 257.040009 | 13442.75 |
| 96  | 663 | 249.119995 | 13435.25 | 108 | 668 | 257.76001  | 13442.75 |
| 97  | 663 | 249.839996 | 13435.25 | 109 | 668 | 258.480011 | 13442.75 |
| 98  | 663 | 250.559998 | 13435.25 | 110 | 668 | 259.200012 | 13442.75 |
| 99  | 663 | 251.279999 | 13435.25 | 111 | 668 | 259.920013 | 13442.75 |
| 100 | 663 | 252        | 13435.25 | 112 | 668 | 260.640015 | 13442.75 |
| 101 | 662 | 252.720001 | 13436    | 113 | 668 | 261.359985 | 13442.75 |
| 102 | 662 | 253.440002 | 13436    | 114 | 668 | 262.079987 | 13442.75 |
| 103 | 662 | 254.160004 | 13436    | 115 | 668 | 262.799988 | 13442.75 |
| 104 | 662 | 254.880005 | 13436    | 116 | 668 | 263.519989 | 13442.75 |
| 105 | 662 | 255.600006 | 13436    | 117 | 669 | 264.23999  | 13442    |
| 106 | 662 | 256.320007 | 13436    | 118 | 669 | 264.959991 | 13442    |
| 106 | 663 | 256.320007 | 13435.25 | 119 | 669 | 265.679993 | 13442    |
| 107 | 663 | 257.040009 | 13435.25 | 120 | 669 | 266.399994 | 13442    |
| 108 | 663 | 257.76001  | 13435.25 | 121 | 669 | 267.119995 | 13442    |
| 109 | 663 | 258.480011 | 13435.25 | 122 | 669 | 267.839996 | 13442    |
| 110 | 663 | 259.200012 | 13435.25 | 123 | 669 | 268.559998 | 13442    |
| 110 | 664 | 259.200012 | 13435.75 | 124 | 669 | 269.279999 | 13442    |
| 110 | 665 | 259.200012 | 13437.75 | 125 | 669 | 270        | 13442    |
| 110 | 666 | 259.200012 | 13438.25 | 126 | 669 | 270.720001 | 13442    |
| 111 | 666 | 259.920013 | 13438.25 | 127 | 669 | 271.440002 | 13442    |
| 112 | 666 | 260.640015 | 13438.25 | 127 | 668 | 271.440002 | 13442.75 |
| 113 | 666 | 261.359985 | 13438.25 | 128 | 668 | 272.160004 | 13442.75 |
| 114 | 666 | 262.079987 | 13438.25 | 129 | 668 | 272.880005 | 13442.75 |
| 115 | 666 | 262.799988 | 13438.25 | 130 | 668 | 273.600006 | 13442.75 |
| 115 | 667 | 262.799988 | 13440.5  | 131 | 668 | 274.320007 | 13442.75 |
| 116 | 667 | 263.519989 | 13440.5  | 132 | 668 | 275.040009 | 13442.75 |

|     |     |            |          |     |     |            |          |
|-----|-----|------------|----------|-----|-----|------------|----------|
| 117 | 667 | 264.23999  | 13440.5  | 133 | 668 | 275.76001  | 13442.75 |
| 117 | 668 | 264.23999  | 13442.75 | 134 | 668 | 276.480011 | 13442.75 |
| 118 | 668 | 264.959991 | 13442.75 | 135 | 668 | 277.200012 | 13442.75 |
| 119 | 668 | 265.679993 | 13442.75 | 136 | 668 | 277.920013 | 13442.75 |
| 120 | 668 | 266.399994 | 13442.75 | 137 | 668 | 278.640015 | 13442.75 |
| 121 | 668 | 267.119995 | 13442.75 | 138 | 668 | 279.359985 | 13442.75 |
| 122 | 668 | 267.839996 | 13442.75 | 139 | 668 | 280.079987 | 13442.75 |
| 123 | 668 | 268.559998 | 13442.75 | 140 | 668 | 280.799988 | 13442.75 |
| 124 | 668 | 269.279999 | 13442.75 | 141 | 668 | 281.519989 | 13442.75 |
| 125 | 668 | 270        | 13442.75 | 142 | 668 | 282.23999  | 13442.75 |
| 126 | 668 | 270.720001 | 13442.75 | 143 | 668 | 282.959991 | 13442.75 |
| 127 | 668 | 271.440002 | 13442.75 | 143 | 667 | 282.959991 | 13440.5  |
| 128 | 668 | 272.160004 | 13442.75 | 144 | 667 | 283.679993 | 13440.5  |
| 129 | 668 | 272.880005 | 13442.75 | 145 | 667 | 284.399994 | 13440.5  |
| 130 | 667 | 273.600006 | 13440.5  | 146 | 667 | 285.119995 | 13440.5  |
| 130 | 668 | 273.600006 | 13442.75 | 147 | 667 | 285.839996 | 13440.5  |
| 131 | 668 | 274.320007 | 13442.75 | 148 | 667 | 286.559998 | 13440.5  |
| 132 | 667 | 275.040009 | 13440.5  | 149 | 667 | 287.279999 | 13440.5  |
| 133 | 667 | 275.76001  | 13440.5  | 150 | 667 | 288        | 13440.5  |
| 134 | 667 | 276.480011 | 13440.5  | 151 | 667 | 288.720001 | 13440.5  |
| 135 | 667 | 277.200012 | 13440.5  | 151 | 666 | 288.720001 | 13438.25 |
| 136 | 667 | 277.920013 | 13440.5  | 152 | 666 | 289.440002 | 13438.25 |
| 137 | 667 | 278.640015 | 13440.5  | 153 | 666 | 290.160004 | 13438.25 |
| 138 | 667 | 279.359985 | 13440.5  | 154 | 666 | 290.880005 | 13438.25 |
| 139 | 667 | 280.079987 | 13440.5  | 155 | 666 | 291.600006 | 13438.25 |
| 140 | 667 | 280.799988 | 13440.5  | 156 | 666 | 292.320007 | 13438.25 |
| 141 | 666 | 281.519989 | 13438.25 | 157 | 666 | 293.040009 | 13438.25 |
| 142 | 665 | 282.23999  | 13437.75 | 158 | 666 | 293.76001  | 13438.25 |
| 143 | 665 | 282.959991 | 13437.75 | 158 | 665 | 293.76001  | 13437.75 |
| 144 | 664 | 283.679993 | 13435.75 | 159 | 665 | 294.480011 | 13437.75 |
| 145 | 664 | 284.399994 | 13435.75 | 160 | 665 | 295.200012 | 13437.75 |
| 145 | 665 | 284.399994 | 13437.75 | 161 | 665 | 295.920013 | 13437.75 |
| 146 | 665 | 285.119995 | 13437.75 | 162 | 665 | 296.640015 | 13437.75 |
| 147 | 665 | 285.839996 | 13437.75 | 163 | 665 | 297.359985 | 13437.75 |
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| 287 | 635 | 26.639999 | 13418    | 279 | 642 | 20.879999 | 13422    |
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| 294 | 633 | 31.68     | 13415.25 | 286 | 642 | 25.92     | 13422    |
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| 298 | 633 | 34.560001 | 13415.25 | 290 | 642 | 28.799999 | 13422    |
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| 317 | 633 | 48.240002 | 13415.25 | 306 | 639 | 40.32     | 13423    |
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| 322 | 633 | 51.84     | 13415.25 | 311 | 640 | 43.919998 | 13422    |
| 323 | 633 | 52.560001 | 13415.25 | 312 | 641 | 44.639999 | 13422.75 |
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| 353 | 631 | 74.160004 | 13415.5  | 341 | 639 | 65.519997 | 13423    |
| 354 | 631 | 74.879997 | 13415.5  | 342 | 639 | 66.239998 | 13423    |
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| 357 | 631 | 77.040001 | 13415.5  | 344 | 638 | 67.68     | 13422.5  |
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| 375 | 634 | 90         | 13417.5  | 364 | 637 | 82.080002  | 13420.5 |
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| 378 | 634 | 92.160004  | 13417.5  | 367 | 637 | 84.239998  | 13420.5 |
| 379 | 634 | 92.879997  | 13417.5  | 368 | 637 | 84.959999  | 13420.5 |
| 380 | 634 | 93.599998  | 13417.5  | 369 | 637 | 85.68      | 13420.5 |
| 381 | 634 | 94.32      | 13417.5  | 370 | 637 | 86.400002  | 13420.5 |
| 382 | 634 | 95.040001  | 13417.5  | 371 | 637 | 87.120003  | 13420.5 |
| 383 | 634 | 95.760002  | 13417.5  | 372 | 637 | 87.839996  | 13420.5 |
| 383 | 635 | 95.760002  | 13418    | 373 | 637 | 88.559998  | 13420.5 |
| 384 | 635 | 96.480003  | 13418    | 374 | 637 | 89.279999  | 13420.5 |
| 385 | 635 | 97.199997  | 13418    | 375 | 638 | 90         | 13422.5 |
| 386 | 635 | 97.919998  | 13418    | 376 | 638 | 90.720001  | 13422.5 |
| 387 | 635 | 98.639999  | 13418    | 377 | 638 | 91.440002  | 13422.5 |
| 388 | 635 | 99.360001  | 13418    | 378 | 638 | 92.160004  | 13422.5 |
| 389 | 635 | 100.080002 | 13418    | 379 | 638 | 92.879997  | 13422.5 |
| 390 | 635 | 100.800003 | 13418    | 380 | 638 | 93.599998  | 13422.5 |
| 391 | 634 | 101.519997 | 13417.5  | 380 | 637 | 93.599998  | 13420.5 |
| 392 | 634 | 102.239998 | 13417.5  | 381 | 637 | 94.32      | 13420.5 |
| 393 | 634 | 102.959999 | 13417.5  | 382 | 637 | 95.040001  | 13420.5 |
| 394 | 634 | 103.68     | 13417.5  | 383 | 637 | 95.760002  | 13420.5 |
| 394 | 635 | 103.68     | 13418    | 384 | 637 | 96.480003  | 13420.5 |
| 395 | 635 | 104.400002 | 13418    | 385 | 637 | 97.199997  | 13420.5 |
| 396 | 635 | 105.120003 | 13418    | 386 | 637 | 97.919998  | 13420.5 |
| 397 | 635 | 105.839996 | 13418    | 387 | 637 | 98.639999  | 13420.5 |
| 398 | 635 | 106.559998 | 13418    | 388 | 637 | 99.360001  | 13420.5 |
| 399 | 635 | 107.279999 | 13418    | 389 | 637 | 100.080002 | 13420.5 |
| 400 | 635 | 108        | 13418    | 390 | 637 | 100.800003 | 13420.5 |
| 401 | 635 | 108.720001 | 13418    | 391 | 637 | 101.519997 | 13420.5 |
| 402 | 635 | 109.440002 | 13418    | 392 | 638 | 102.239998 | 13422.5 |
| 403 | 635 | 110.160004 | 13418    | 393 | 638 | 102.959999 | 13422.5 |
| 404 | 635 | 110.879997 | 13418    | 394 | 638 | 103.68     | 13422.5 |
| 405 | 635 | 111.599998 | 13418    | 395 | 638 | 104.400002 | 13422.5 |

|     |     |            |          |     |     |            |          |
|-----|-----|------------|----------|-----|-----|------------|----------|
| 406 | 635 | 112.32     | 13418    | 396 | 638 | 105.120003 | 13422.5  |
| 407 | 635 | 113.040001 | 13418    | 397 | 639 | 105.839996 | 13423    |
| 408 | 634 | 113.760002 | 13417.5  | 398 | 639 | 106.559998 | 13423    |
| 409 | 634 | 114.480003 | 13417.5  | 399 | 639 | 107.279999 | 13423    |
| 410 | 634 | 115.199997 | 13417.5  | 400 | 639 | 108        | 13423    |
| 411 | 634 | 115.919998 | 13417.5  | 401 | 639 | 108.720001 | 13423    |
| 412 | 634 | 116.639999 | 13417.5  | 402 | 640 | 109.440002 | 13422    |
| 413 | 634 | 117.360001 | 13417.5  | 403 | 640 | 110.160004 | 13422    |
| 413 | 635 | 117.360001 | 13418    | 404 | 640 | 110.879997 | 13422    |
| 414 | 635 | 118.080002 | 13418    | 405 | 640 | 111.599998 | 13422    |
| 415 | 635 | 118.800003 | 13418    | 406 | 640 | 112.32     | 13422    |
| 416 | 635 | 119.519997 | 13418    | 407 | 640 | 113.040001 | 13422    |
| 416 | 636 | 119.519997 | 13420    | 408 | 640 | 113.760002 | 13422    |
| 417 | 636 | 120.239998 | 13420    | 409 | 640 | 114.480003 | 13422    |
| 417 | 637 | 120.239998 | 13420.5  | 410 | 640 | 115.199997 | 13422    |
| 418 | 637 | 120.959999 | 13420.5  | 411 | 640 | 115.919998 | 13422    |
| 419 | 637 | 121.68     | 13420.5  | 412 | 640 | 116.639999 | 13422    |
| 420 | 637 | 122.400002 | 13420.5  | 413 | 640 | 117.360001 | 13422    |
| 421 | 637 | 123.120003 | 13420.5  | 414 | 640 | 118.080002 | 13422    |
| 422 | 637 | 123.839996 | 13420.5  | 415 | 640 | 118.800003 | 13422    |
| 423 | 637 | 124.559998 | 13420.5  | 416 | 640 | 119.519997 | 13422    |
| 423 | 638 | 124.559998 | 13422.5  | 417 | 640 | 120.239998 | 13422    |
| 424 | 638 | 125.279999 | 13422.5  | 418 | 640 | 120.959999 | 13422    |
| 425 | 638 | 126        | 13422.5  | 419 | 640 | 121.68     | 13422    |
| 426 | 638 | 126.720001 | 13422.5  | 420 | 640 | 122.400002 | 13422    |
| 427 | 638 | 127.440002 | 13422.5  | 421 | 640 | 123.120003 | 13422    |
| 427 | 639 | 127.440002 | 13423    | 422 | 641 | 123.839996 | 13422.75 |
| 428 | 639 | 128.160004 | 13423    | 422 | 642 | 123.839996 | 13422    |
| 429 | 639 | 128.880005 | 13423    | 423 | 642 | 124.559998 | 13422    |
| 430 | 639 | 129.600006 | 13423    | 423 | 641 | 124.559998 | 13422.75 |
| 431 | 639 | 130.320007 | 13423    | 424 | 641 | 125.279999 | 13422.75 |
| 432 | 639 | 131.039993 | 13423    | 425 | 641 | 126        | 13422.75 |
| 433 | 639 | 131.759995 | 13423    | 426 | 641 | 126.720001 | 13422.75 |
| 433 | 640 | 131.759995 | 13422    | 427 | 641 | 127.440002 | 13422.75 |
| 434 | 640 | 132.479996 | 13422    | 428 | 641 | 128.160004 | 13422.75 |
| 435 | 640 | 133.199997 | 13422    | 429 | 641 | 128.880005 | 13422.75 |
| 435 | 641 | 133.199997 | 13422.75 | 430 | 641 | 129.600006 | 13422.75 |
| 436 | 641 | 133.919998 | 13422.75 | 431 | 641 | 130.320007 | 13422.75 |
| 437 | 641 | 134.639999 | 13422.75 | 432 | 641 | 131.039993 | 13422.75 |
| 438 | 641 | 135.360001 | 13422.75 | 433 | 641 | 131.759995 | 13422.75 |
| 438 | 642 | 135.360001 | 13422    | 434 | 641 | 132.479996 | 13422.75 |
| 439 | 642 | 136.080002 | 13422    | 435 | 641 | 133.199997 | 13422.75 |
| 440 | 642 | 136.800003 | 13422    | 436 | 641 | 133.919998 | 13422.75 |
| 441 | 641 | 137.520004 | 13422.75 | 437 | 642 | 134.639999 | 13422    |
| 442 | 641 | 138.240005 | 13422.75 | 438 | 642 | 135.360001 | 13422    |
| 443 | 641 | 138.960007 | 13422.75 | 439 | 643 | 136.080002 | 13424    |
| 444 | 640 | 139.679993 | 13422    | 440 | 643 | 136.800003 | 13424    |
| 445 | 640 | 140.399994 | 13422    | 441 | 644 | 137.520004 | 13426    |
| 446 | 639 | 141.119995 | 13423    | 442 | 644 | 138.240005 | 13426    |
| 447 | 639 | 141.839996 | 13423    | 443 | 644 | 138.960007 | 13426    |

|     |     |            |          |     |     |            |          |
|-----|-----|------------|----------|-----|-----|------------|----------|
| 448 | 639 | 142.559998 | 13423    | 444 | 644 | 139.679993 | 13426    |
| 449 | 638 | 143.279999 | 13422.5  | 445 | 644 | 140.399994 | 13426    |
| 450 | 638 | 144        | 13422.5  | 446 | 644 | 141.119995 | 13426    |
| 451 | 638 | 144.720001 | 13422.5  | 447 | 644 | 141.839996 | 13426    |
| 452 | 638 | 145.440002 | 13422.5  | 448 | 644 | 142.559998 | 13426    |
| 453 | 638 | 146.160004 | 13422.5  | 449 | 644 | 143.279999 | 13426    |
| 453 | 639 | 146.160004 | 13423    | 450 | 644 | 144        | 13426    |
| 453 | 640 | 146.160004 | 13422    | 451 | 644 | 144.720001 | 13426    |
| 454 | 640 | 146.880005 | 13422    | 452 | 644 | 145.440002 | 13426    |
| 455 | 640 | 147.600006 | 13422    | 453 | 644 | 146.160004 | 13426    |
| 455 | 641 | 147.600006 | 13422.75 | 454 | 644 | 146.880005 | 13426    |
| 456 | 641 | 148.320007 | 13422.75 | 455 | 644 | 147.600006 | 13426    |
| 457 | 641 | 149.039993 | 13422.75 | 456 | 645 | 148.320007 | 13426.5  |
| 457 | 642 | 149.039993 | 13422    | 457 | 645 | 149.039993 | 13426.5  |
| 458 | 642 | 149.759995 | 13422    | 458 | 645 | 149.759995 | 13426.5  |
| 459 | 642 | 150.479996 | 13422    | 459 | 646 | 150.479996 | 13425.75 |
| 460 | 642 | 151.199997 | 13422    | 460 | 646 | 151.199997 | 13425.75 |
| 461 | 642 | 151.919998 | 13422    | 461 | 646 | 151.919998 | 13425.75 |
| 462 | 642 | 152.639999 | 13422    | 462 | 647 | 152.639999 | 13426.25 |
| 463 | 642 | 153.360001 | 13422    | 463 | 647 | 153.360001 | 13426.25 |
| 464 | 642 | 154.080002 | 13422    | 464 | 647 | 154.080002 | 13426.25 |
| 465 | 642 | 154.800003 | 13422    | 465 | 648 | 154.800003 | 13425.5  |
| 466 | 642 | 155.520004 | 13422    | 466 | 648 | 155.520004 | 13425.5  |
| 467 | 642 | 156.240005 | 13422    | 467 | 648 | 156.240005 | 13425.5  |
| 468 | 642 | 156.960007 | 13422    | 468 | 648 | 156.960007 | 13425.5  |
| 469 | 642 | 157.679993 | 13422    | 469 | 649 | 157.679993 | 13427.75 |
| 470 | 642 | 158.399994 | 13422    | 470 | 649 | 158.399994 | 13427.75 |
| 471 | 642 | 159.119995 | 13422    | 471 | 649 | 159.119995 | 13427.75 |
| 472 | 642 | 159.839996 | 13422    | 472 | 650 | 159.839996 | 13428.25 |
| 473 | 642 | 160.559998 | 13422    | 473 | 650 | 160.559998 | 13428.25 |
| 474 | 642 | 161.279999 | 13422    | 474 | 650 | 161.279999 | 13428.25 |
| 475 | 642 | 162        | 13422    | 475 | 650 | 162        | 13428.25 |
| 476 | 642 | 162.720001 | 13422    | 476 | 650 | 162.720001 | 13428.25 |
| 477 | 642 | 163.440002 | 13422    | 477 | 650 | 163.440002 | 13428.25 |
| 478 | 642 | 164.160004 | 13422    | 478 | 651 | 164.160004 | 13430.25 |
| 478 | 643 | 164.160004 | 13424    | 479 | 652 | 164.880005 | 13430.75 |
| 479 | 643 | 164.880005 | 13424    | 480 | 652 | 165.600006 | 13430.75 |
| 480 | 643 | 165.600006 | 13424    | 481 | 652 | 166.320007 | 13430.75 |
| 481 | 643 | 166.320007 | 13424    | 482 | 652 | 167.039993 | 13430.75 |
| 481 | 644 | 166.320007 | 13426    | 483 | 652 | 167.759995 | 13430.75 |
| 482 | 644 | 167.039993 | 13426    | 484 | 653 | 168.479996 | 13433    |
| 483 | 644 | 167.759995 | 13426    | 485 | 653 | 169.199997 | 13433    |
| 484 | 644 | 168.479996 | 13426    | 486 | 653 | 169.919998 | 13433    |
| 485 | 644 | 169.199997 | 13426    | 487 | 654 | 170.639999 | 13432.25 |
| 485 | 645 | 169.199997 | 13426.5  | 488 | 654 | 171.360001 | 13432.25 |
| 486 | 645 | 169.919998 | 13426.5  | 489 | 654 | 172.080002 | 13432.25 |
| 487 | 645 | 170.639999 | 13426.5  | 490 | 654 | 172.800003 | 13432.25 |
| 488 | 645 | 171.360001 | 13426.5  | 491 | 654 | 173.520004 | 13432.25 |
| 489 | 645 | 172.080002 | 13426.5  | 492 | 654 | 174.240005 | 13432.25 |
| 490 | 645 | 172.800003 | 13426.5  | 493 | 654 | 174.960007 | 13432.25 |

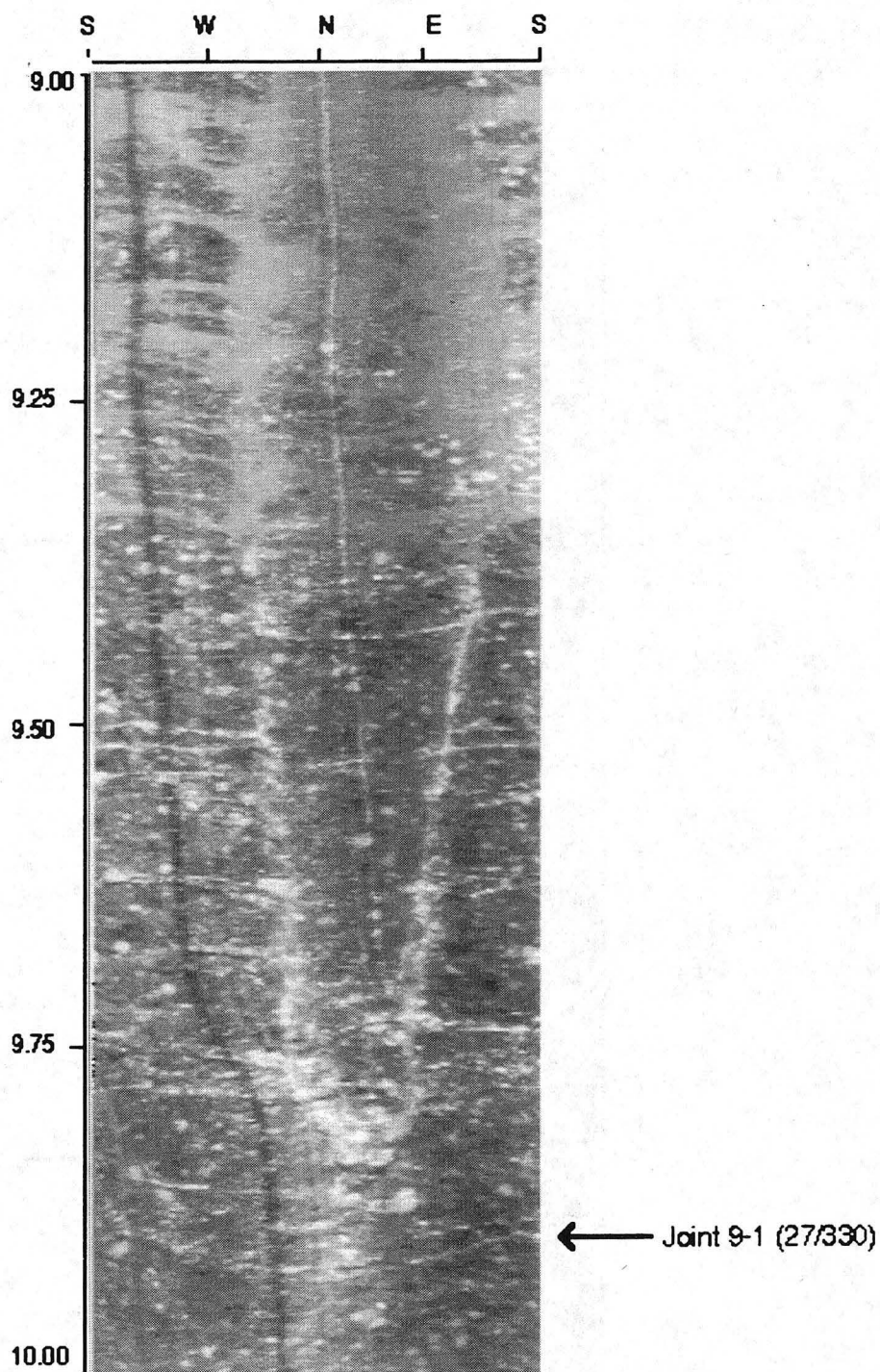
|     |     |            |          |     |     |            |          |
|-----|-----|------------|----------|-----|-----|------------|----------|
| 490 | 646 | 172.800003 | 13425.75 | 494 | 654 | 175.679993 | 13432.25 |
| 491 | 646 | 173.520004 | 13425.75 | 495 | 655 | 176.399994 | 13434.5  |
| 491 | 647 | 173.520004 | 13426.25 | 496 | 655 | 177.119995 | 13434.5  |
| 492 | 647 | 174.240005 | 13426.25 | 497 | 655 | 177.839996 | 13434.5  |
| 492 | 648 | 174.240005 | 13425.5  | 498 | 655 | 178.559998 | 13434.5  |
| 493 | 648 | 174.960007 | 13425.5  | 499 | 655 | 179.279999 | 13434.5  |
| 494 | 648 | 175.679993 | 13425.5  | 500 | 656 | 180        | 13432.25 |
| 494 | 649 | 175.679993 | 13427.75 |     |     |            |          |
| 495 | 649 | 176.399994 | 13427.75 |     |     |            |          |
| 496 | 649 | 177.119995 | 13427.75 |     |     |            |          |
| 497 | 649 | 177.839996 | 13427.75 |     |     |            |          |
| 498 | 649 | 178.559998 | 13427.75 |     |     |            |          |
| 498 | 650 | 178.559998 | 13428.25 |     |     |            |          |
| 499 | 650 | 179.279999 | 13428.25 |     |     |            |          |
| 500 | 649 | 180        | 13427.75 |     |     |            |          |

## B. Unrolled BSS images from boreholes 3-5 and 4-1

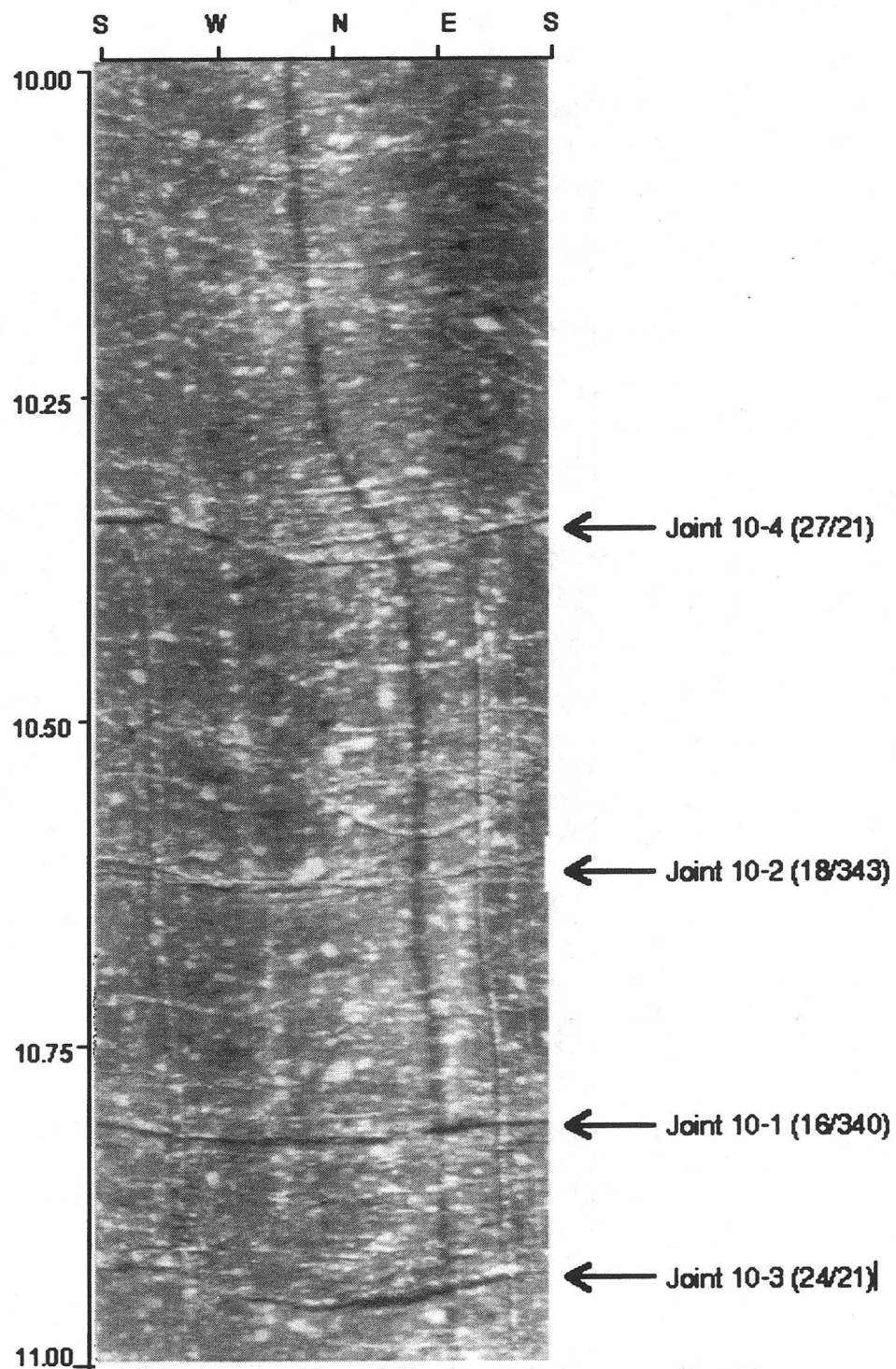
Table B.1 lists the orientations and joint set memberships of all of the joints from boreholes 3-5 and 4-1 which were used in this thesis. The joints are identified in images of the unrolled borehole walls.

Table B.1: List of joints

| Joint Name | From Borehole | Dip & Dip Dir. | Joint Set | Joint Name | From Borehole | Dip & Dip Dir. | Joint Set |
|------------|---------------|----------------|-----------|------------|---------------|----------------|-----------|
| 9-1        | 3-5           | 27/330         | 7         | 17-1       | 3-5           | 18/345         | 1         |
| 10-1       | 3-5           | 16/340         | 1         | 17-2       | 3-5           | 28/311         | 9         |
| 10-2       | 3-5           | 18/343         | 1         | 18-1       | 3-5           | 25/282         | 5         |
| 10-3       | 3-5           | 24/21          | 2         | 19-1       | 3-5           | 14/277         | 4         |
| 10-4       | 3-5           | 27/21          | 2         | 19-2       | 3-5           | 22/266         | 14        |
| 11-1       | 3-5           | 14/2           | 8         | 19-3       | 3-5           | 21/275         | 4         |
| 13-1       | 3-5           | 20/254         | 3         | 19-4       | 3-5           | 23/241         | 6         |
| 13-2       | 3-5           | 24/275         | 4         | 20-1       | 3-5           | 20/270         | 4         |
| 14-1       | 3-5           | 16/250         | 3         | 20-2       | 3-5           | 8/146          | 10        |
| 14-2       | 3-5           | 19/323         | 7         | 20-3       | 3-5           | 20/285         | 5         |
| 14-3       | 3-5           | 27/275         | 4         | 21-1       | 3-5           | 40/116         | 11        |
| 14-4       | 3-5           | 33/244         | 6         | 21-2       | 3-5           | 13/164         | 12        |
| 15-1       | 3-5           | 17/244         | 6         | 21-3       | 3-5           | 7/246          | 13        |
| 15-2       | 3-5           | 22/272         | 4         | 10-1       | 4-1           | 38/244         | -         |
| 15-3       | 3-5           | 47/320         | 7         | 42-1       | 4-1           | 22/120         | -         |
| 15-4       | 3-5           | 16/256         | 15        | 48-1       | 4-1           | 42/325         | -         |
| 15-5       | 3-5           | 33/345         | 1         | 64-1       | 4-1           | 35/336         | -         |

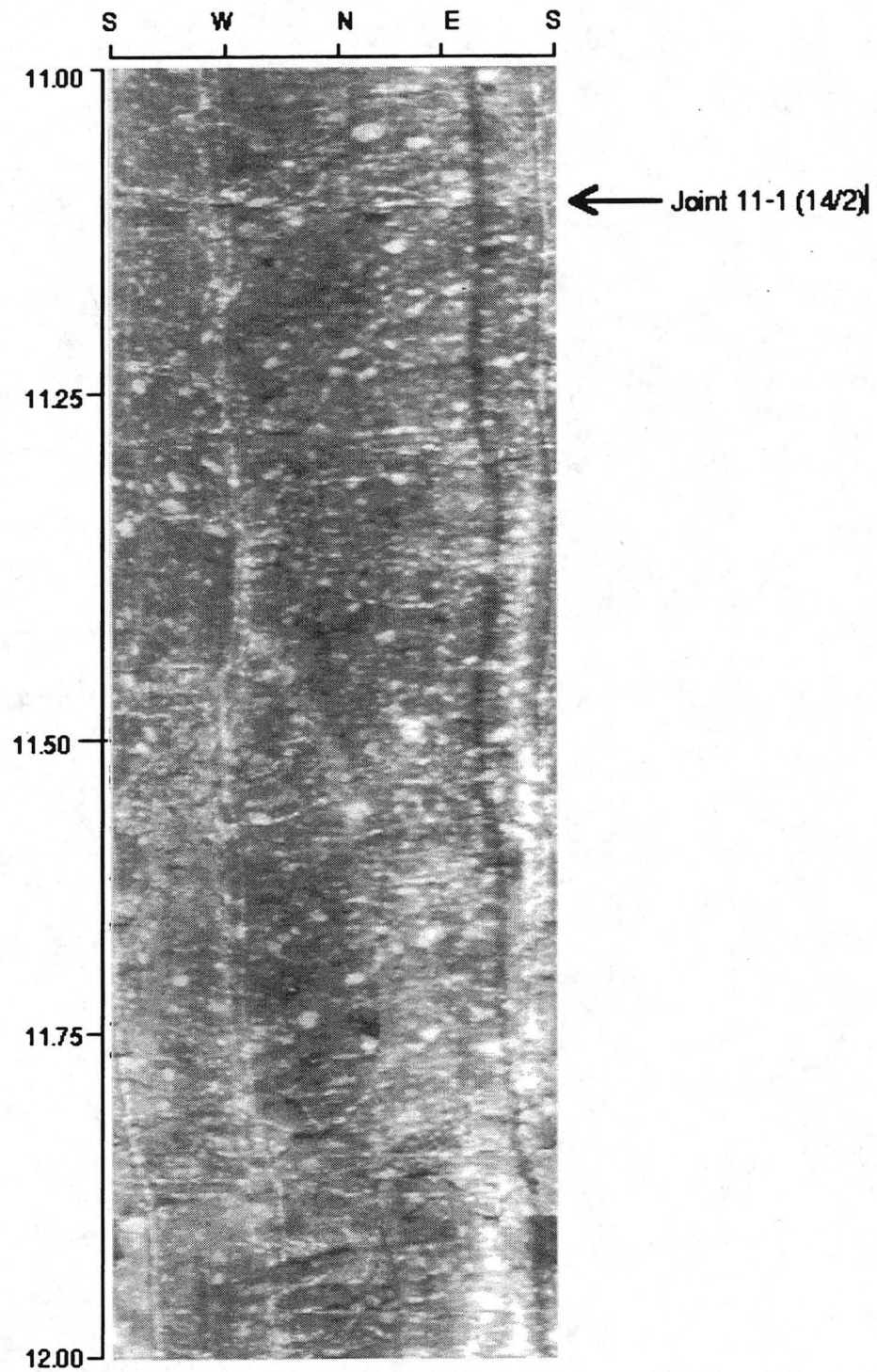


**Figure B.1: Joints in unrolled image of 9 m. interval**

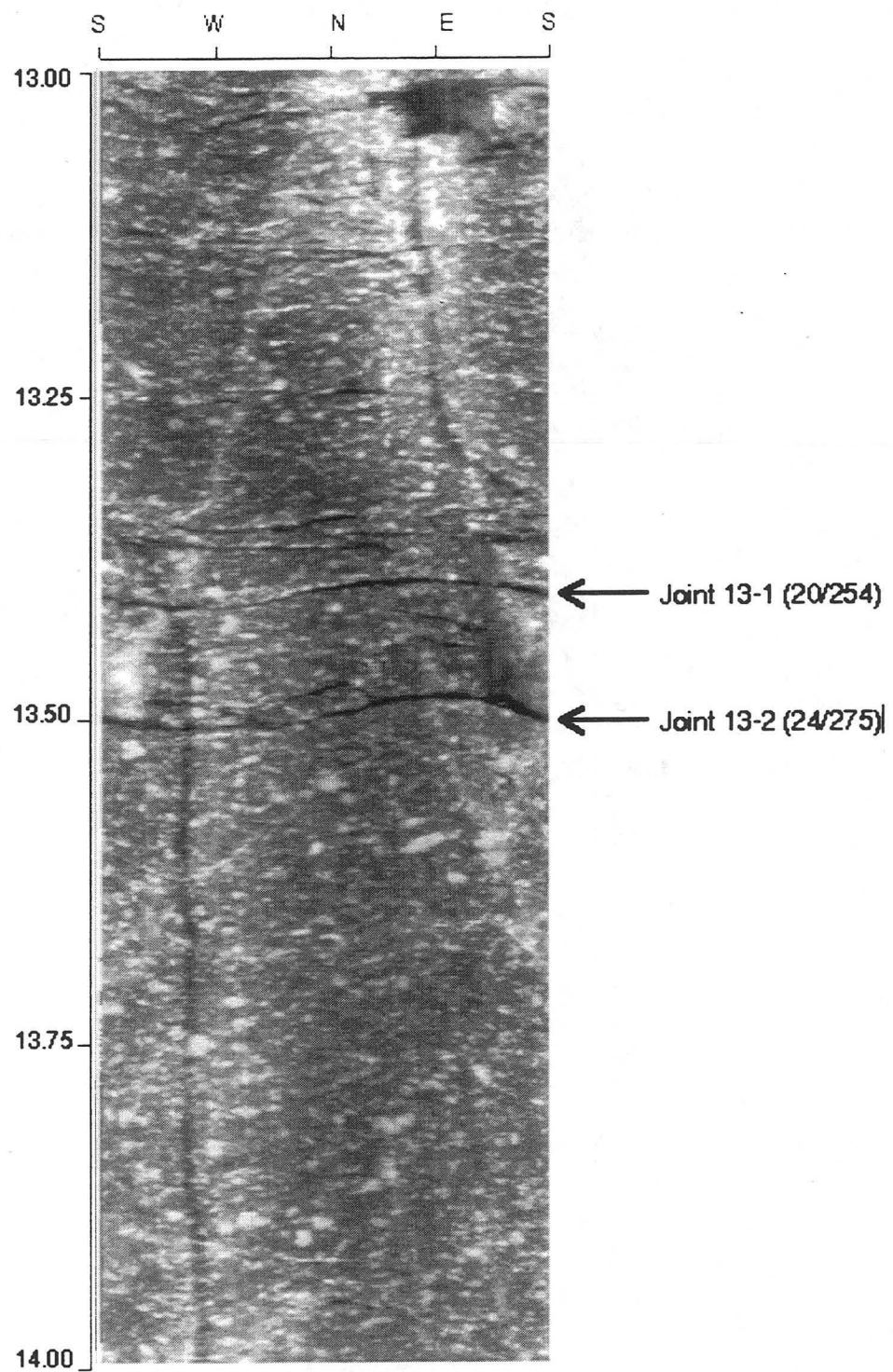


**Figure B.2: Unrolled image of joints in 10 m. interval**



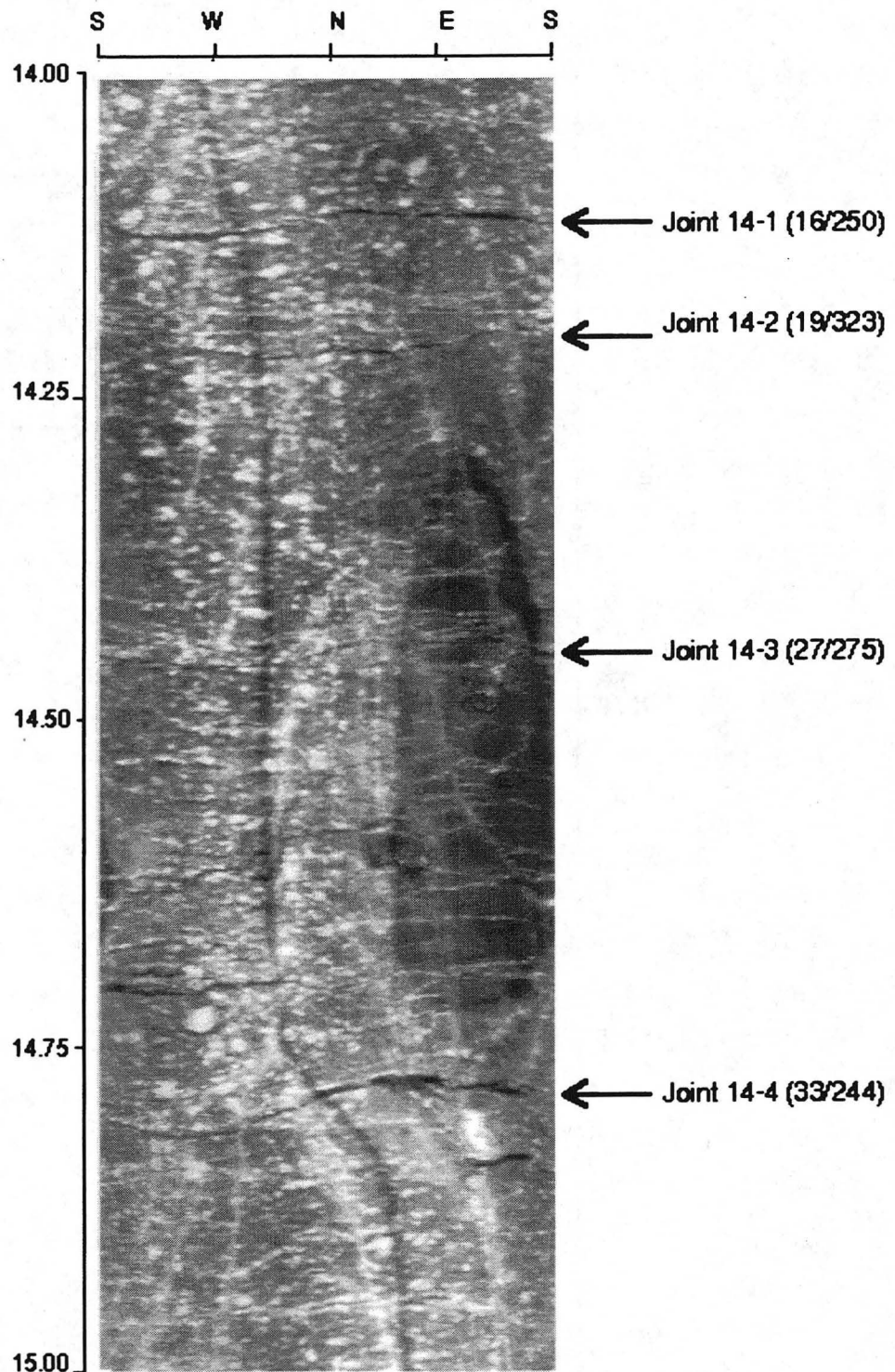


**Figure B.3: Joints in unrolled image of 11 m. interval**

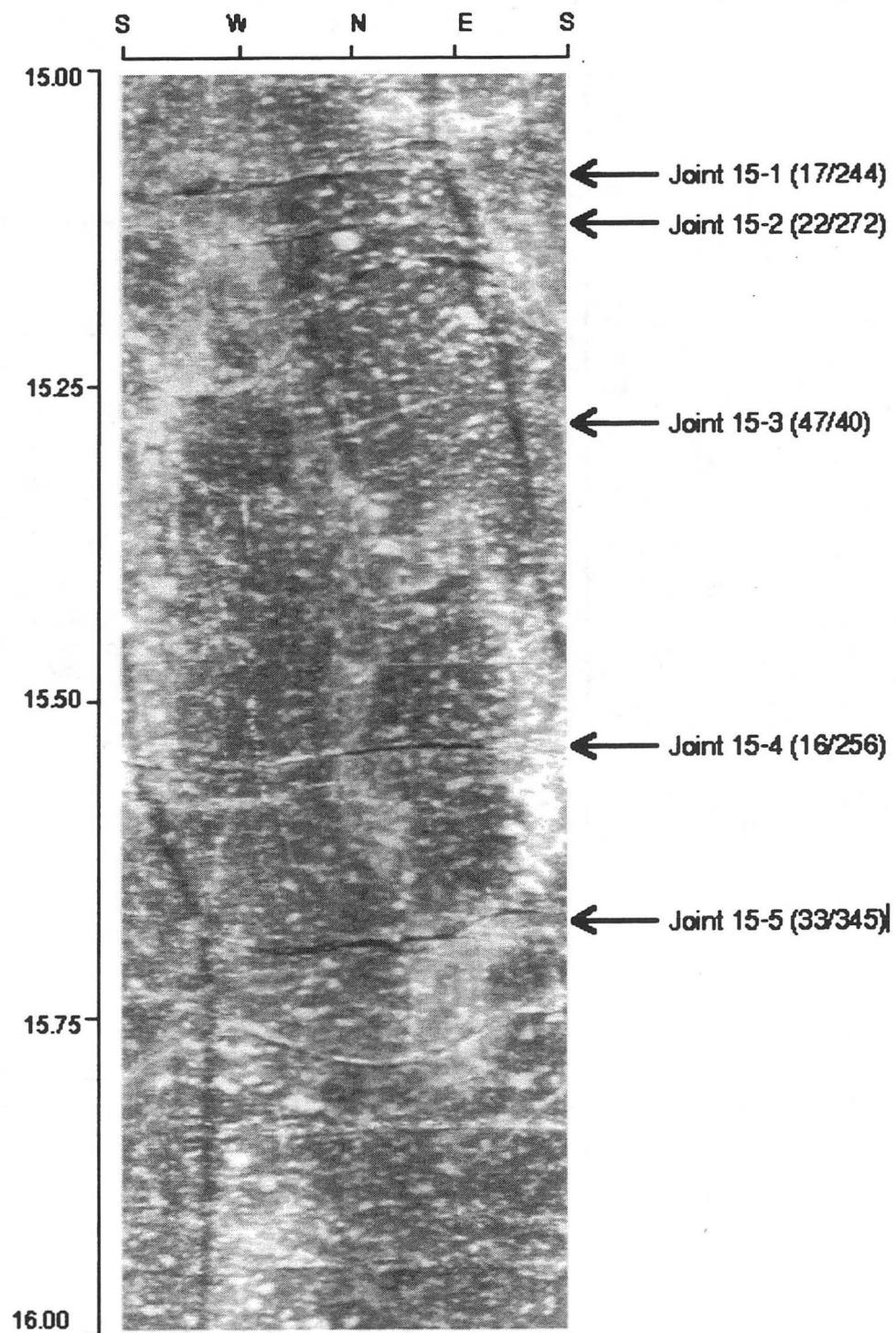


**Figure B.4: Joints in unrolled image of 13 m. interval**

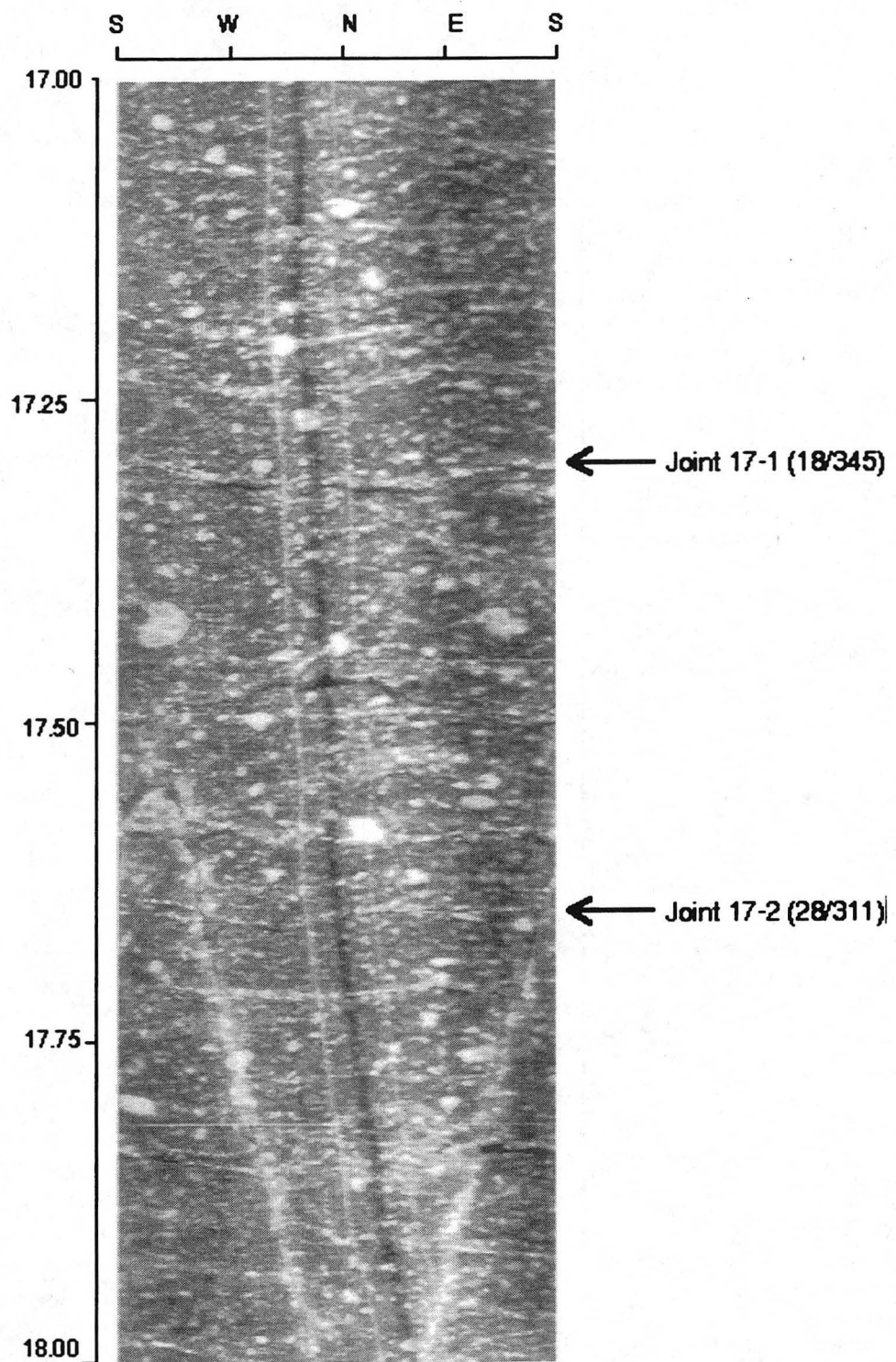




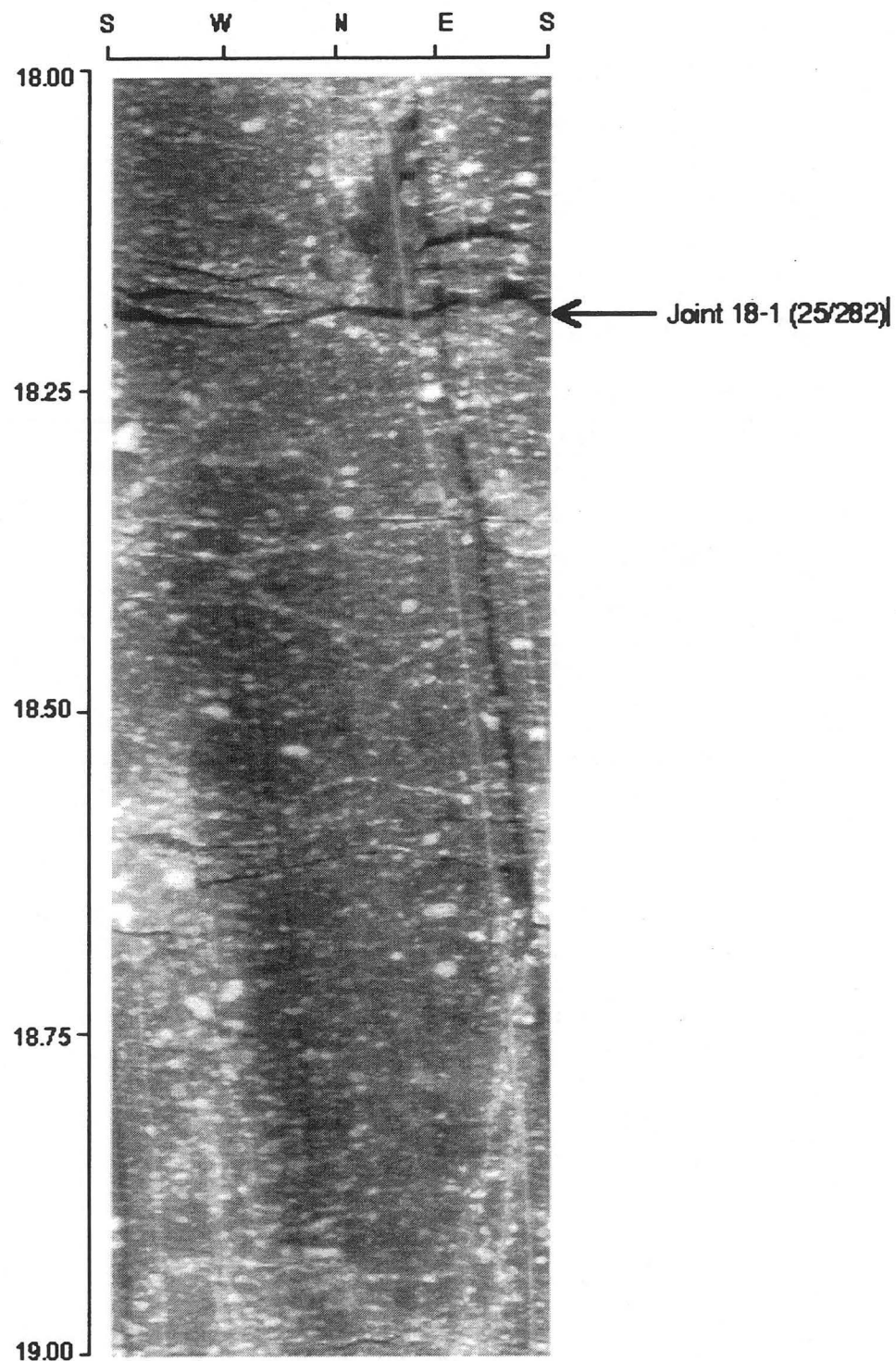
**Figure B.5: Joints in unrolled image of 14 m. interval**



**Figure B.6: Joints in unrolled Image of 15 m. interval**

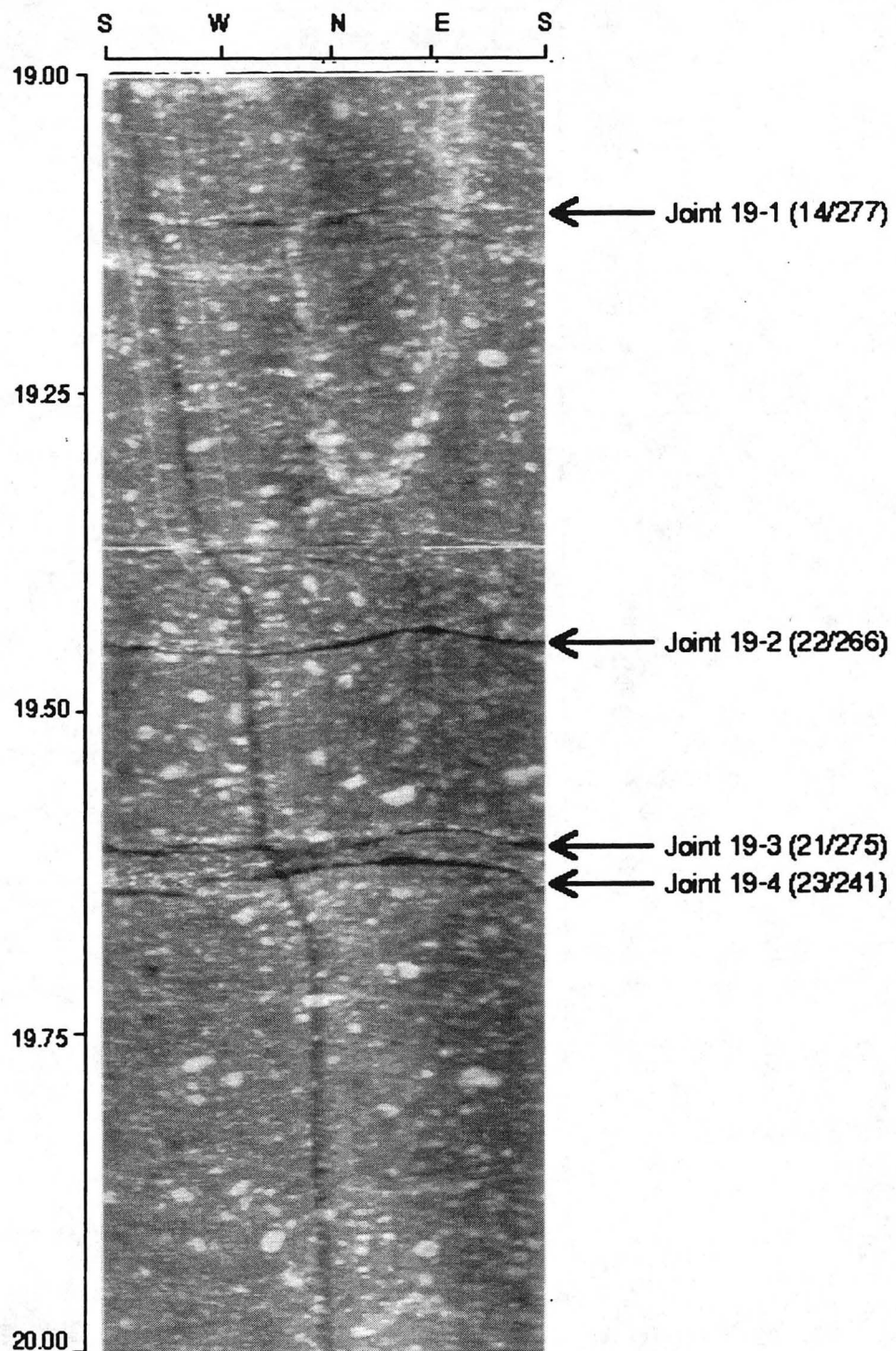


**Figure B.7: Joints in unrolled image of 17 m. interval**

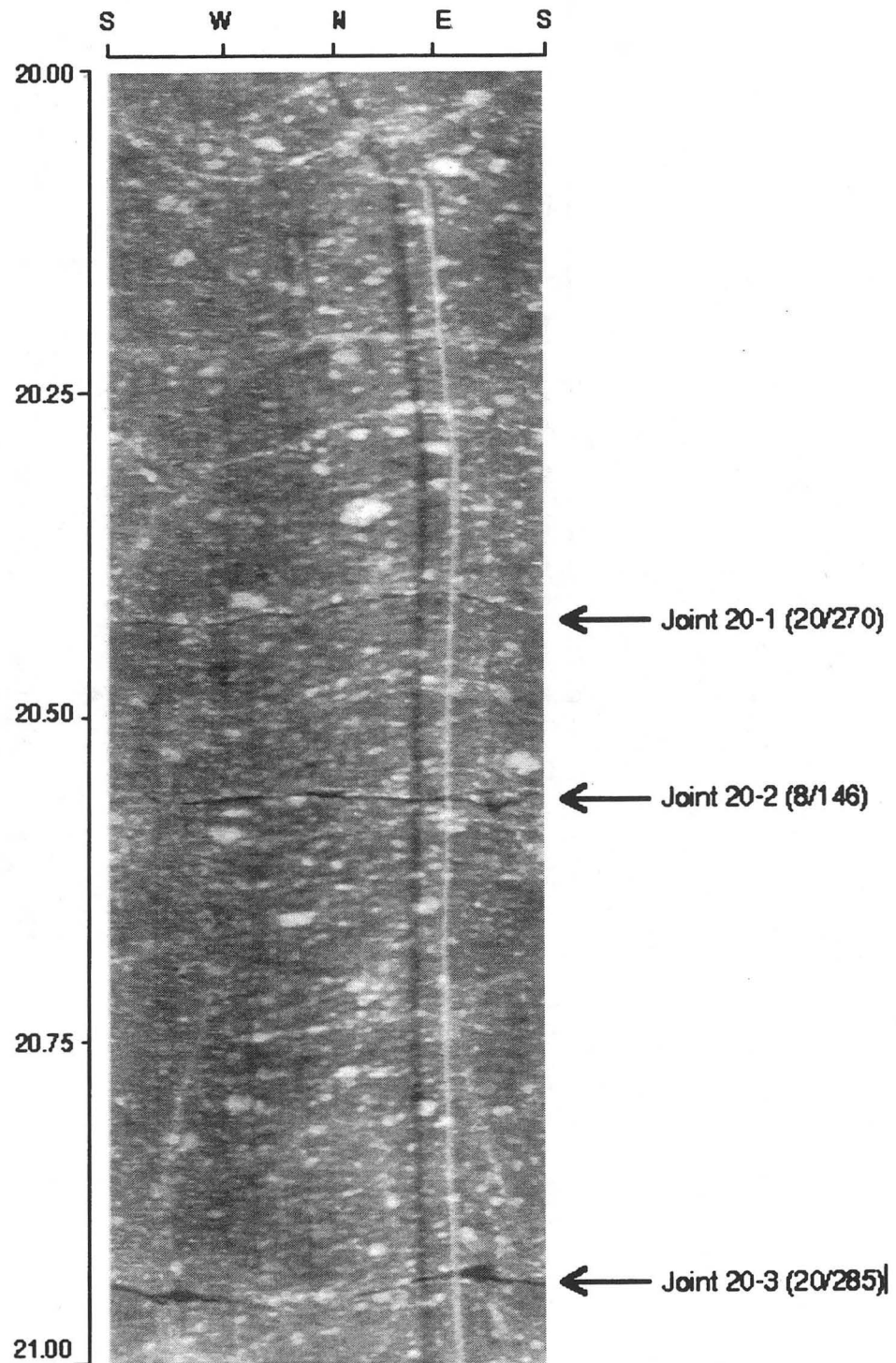


**Figure B.8: Joints in unrolled Image of 18 m. interval**

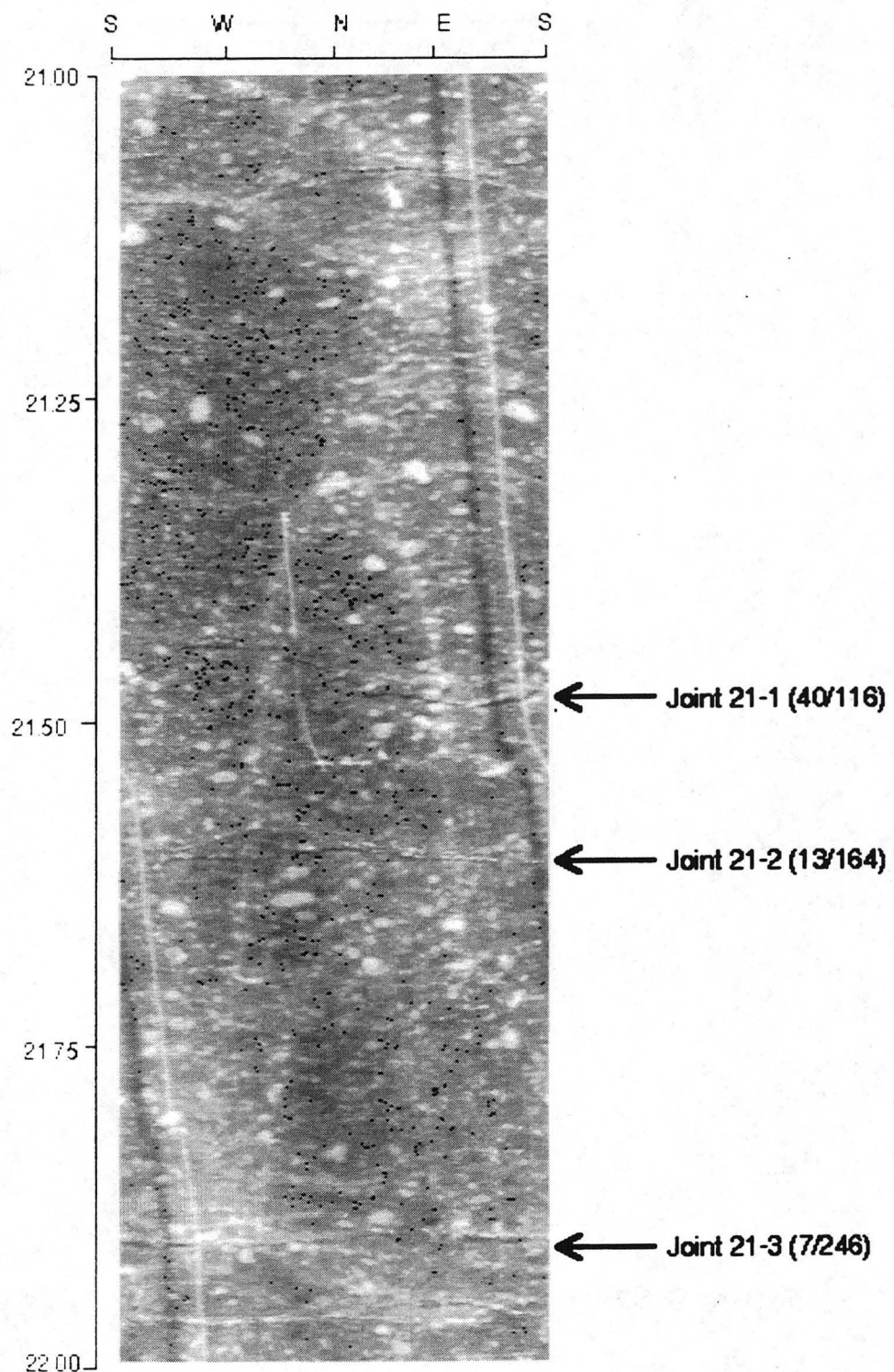




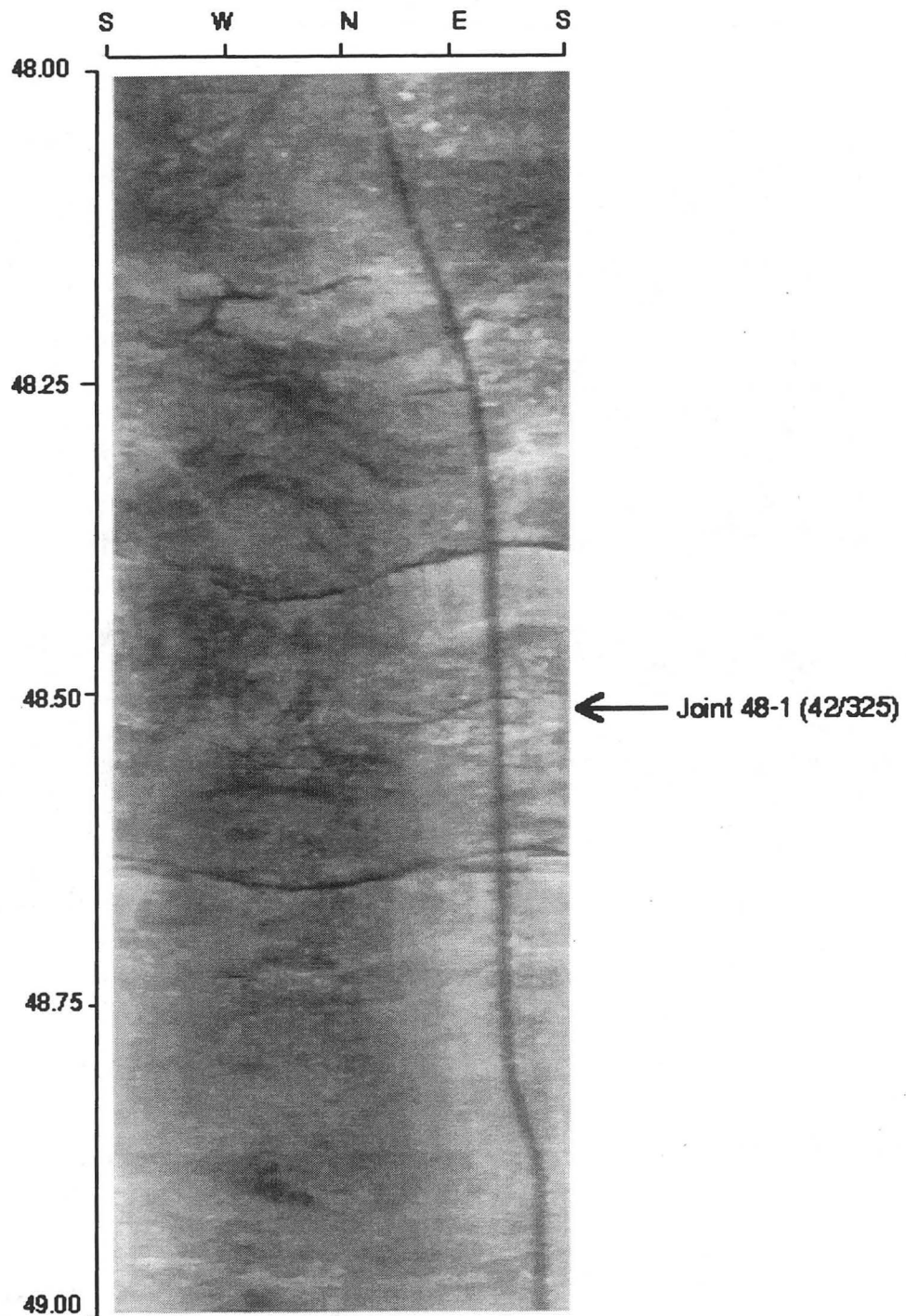
**Figure B.9: Joints in unrolled image of 19 m. interval**



**Figure B.10: Joints in unrolled image of 20 m. interval**



**Figure B.11: Joints in unrolled image of 21 m. interval**



**Figure B.12: Unrolled borehole wall image of 48 m. interval**





Figure B.13: Unrolled borehole wall image of 64 m. interval

### C. Verification of Renger's envelope algorithm

Results from the analysis of the profile of a smooth plane intersected by a vertical borehole using envelope.c are presented in Figure C.1 below.

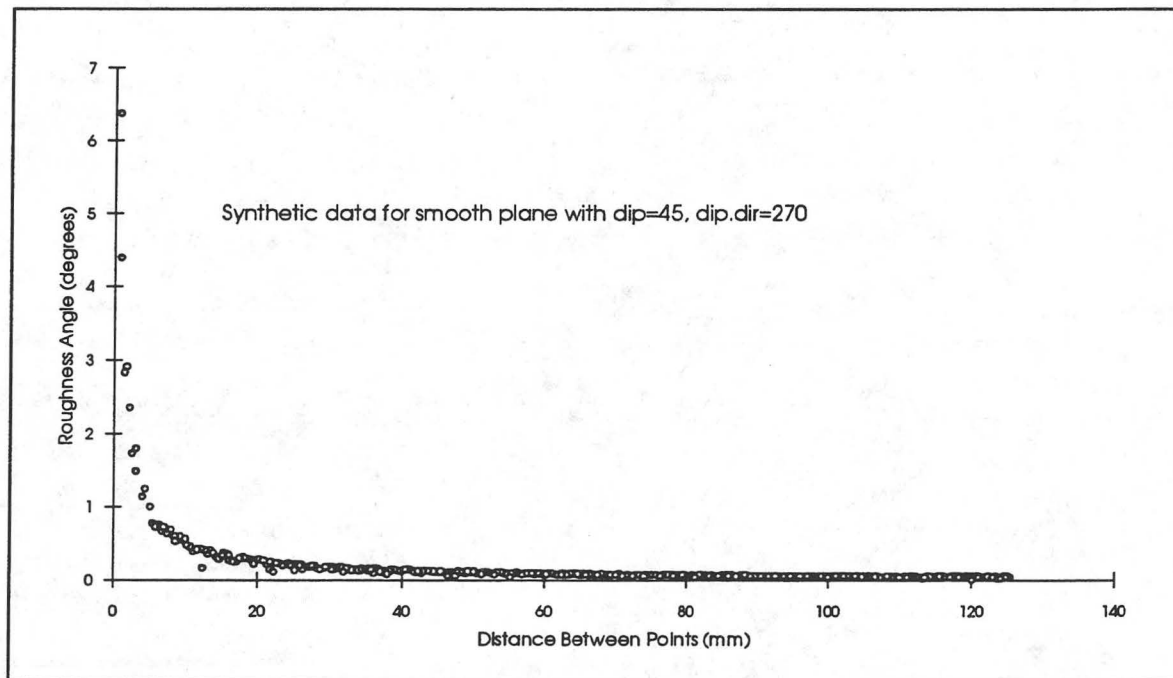


Figure C.1: Verification of Renger's envelope algorithm

#### D. Examples of Rengers envelopes of joints in borehole 3-5

Examples of Rengers envelopes for joints in borehole 3-5 which were computed using envelope.c are presented below.

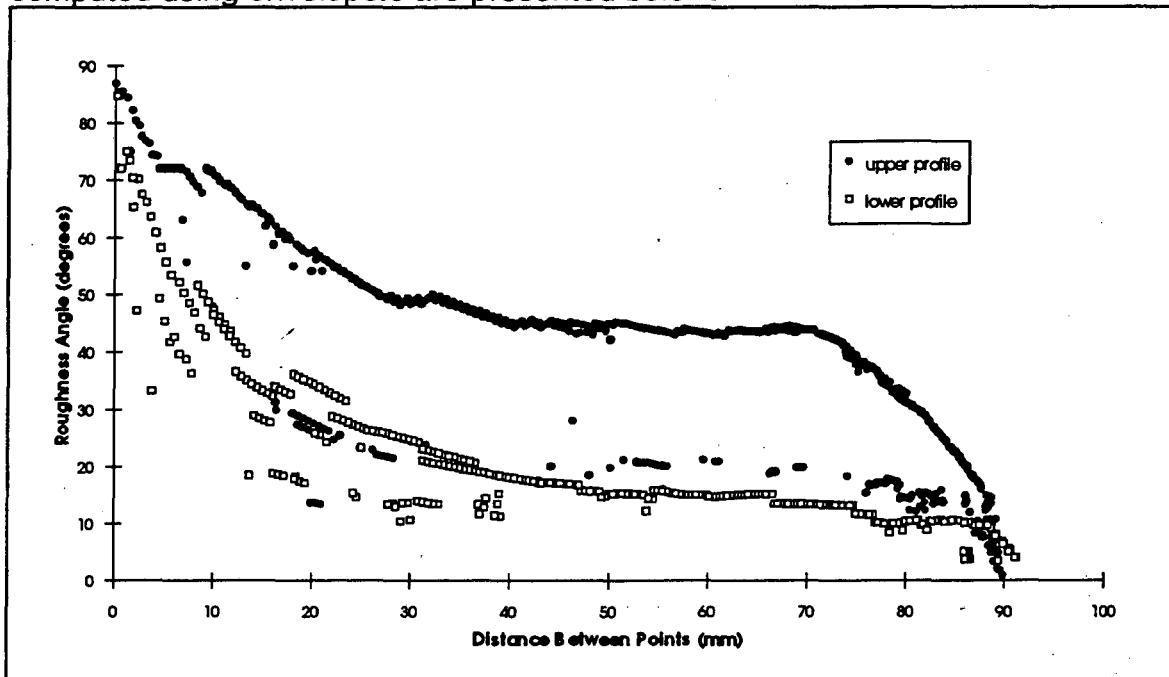


Figure D.1: Rengers envelopes for joint 10-2

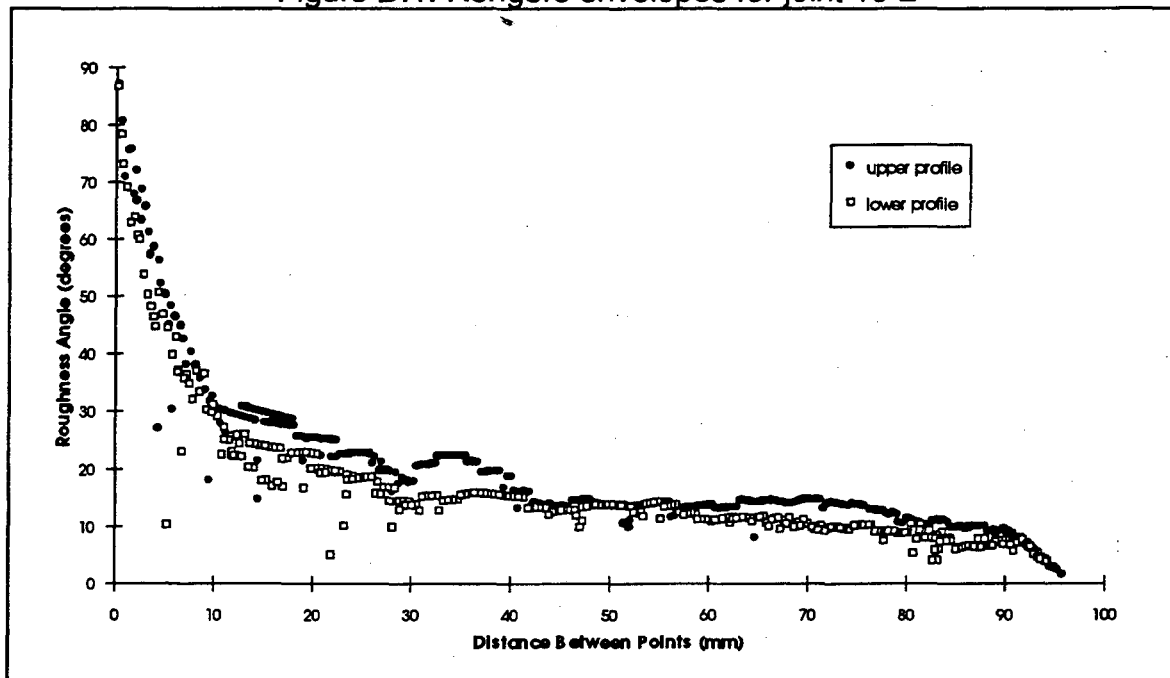


Figure D.2: Rengers envelopes for joint 10-3

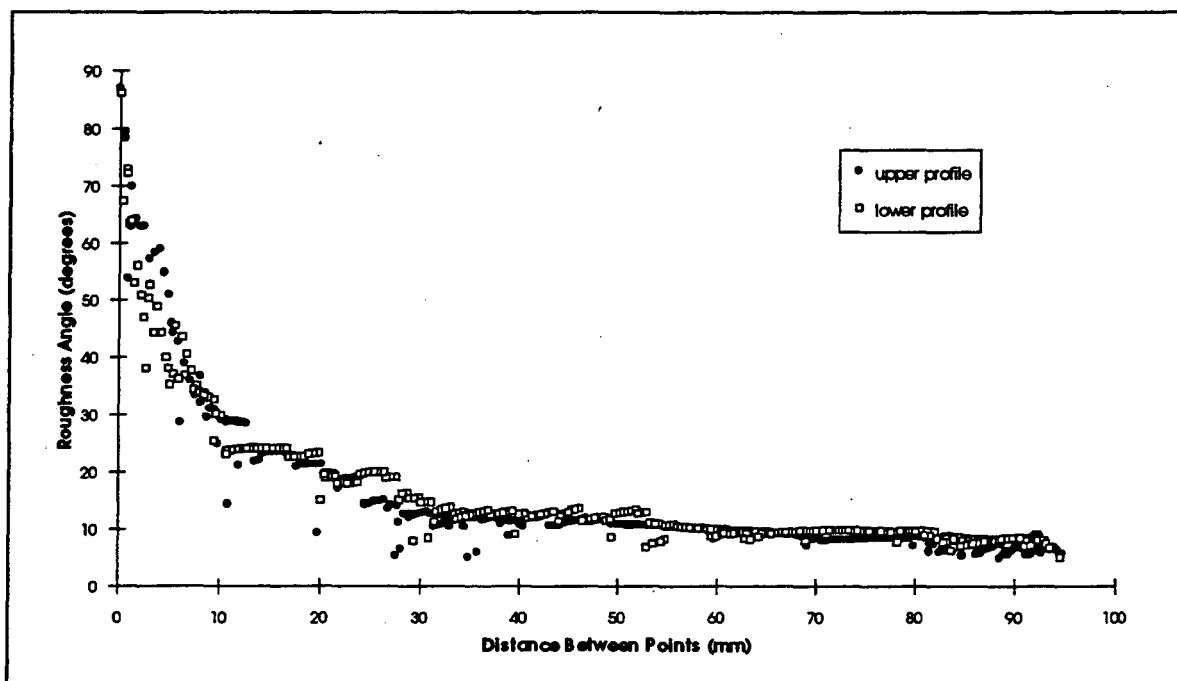


Figure D.3: Rengers envelopes for joint 10-4

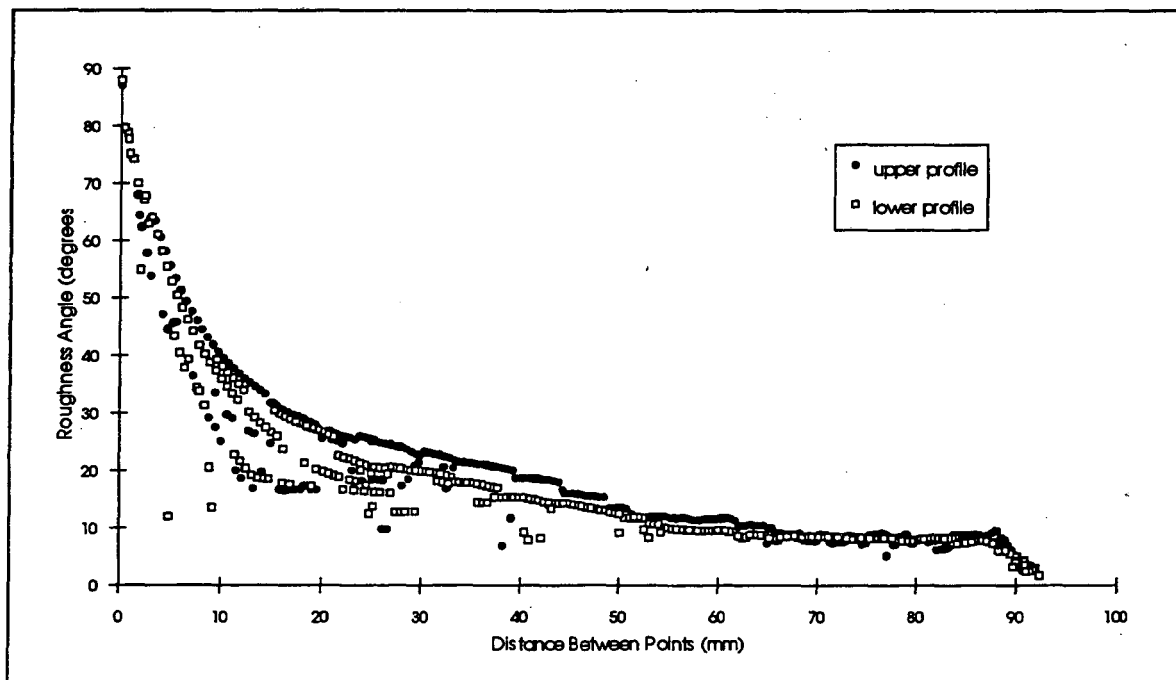


Figure D.4: Rengers envelopes for joint 14-1

### E. Verification of anisotropy analysis algorithm

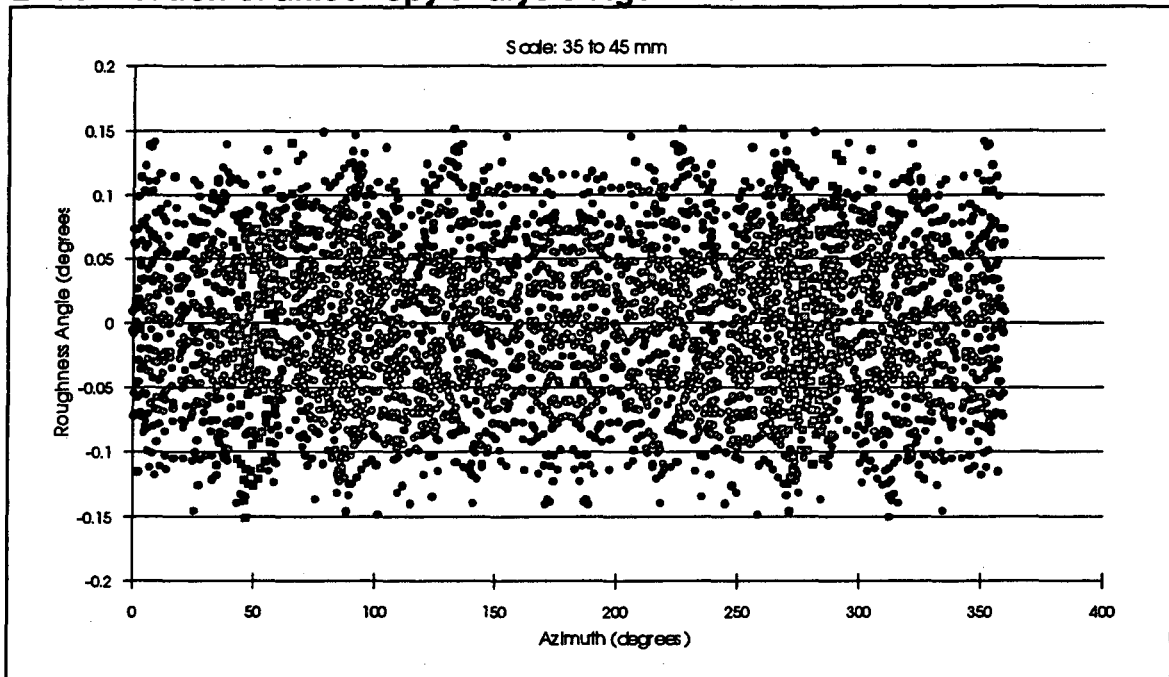


Figure E.1: Verification of anisotropy analysis algorithm for test case 1

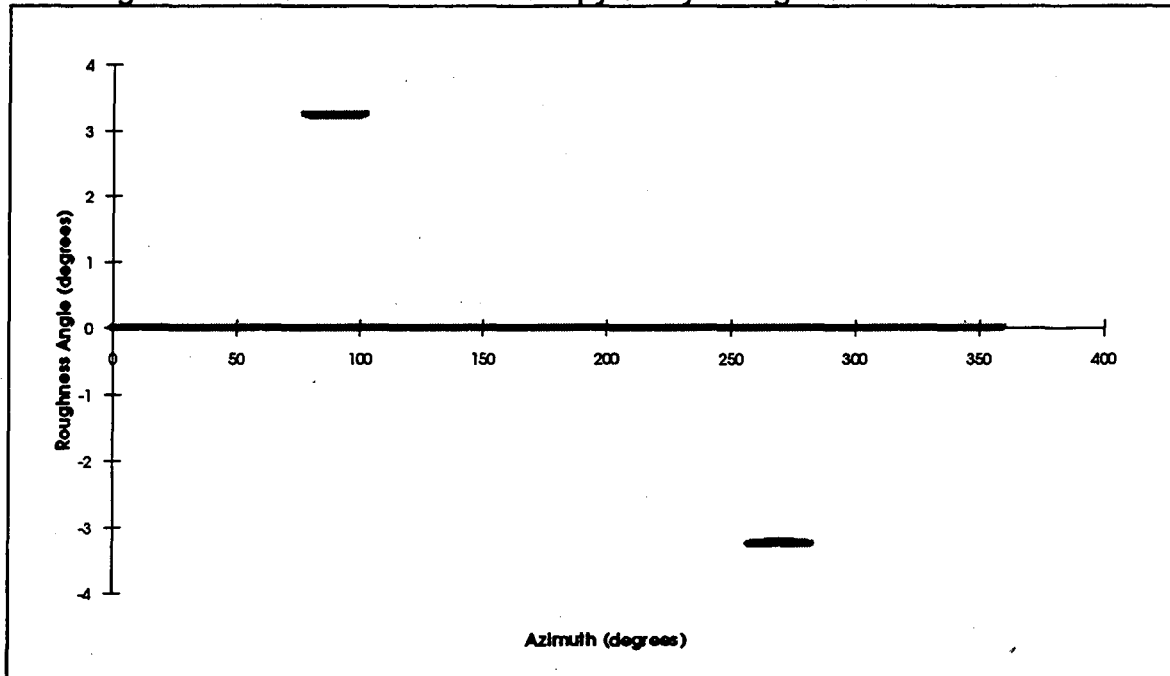


Figure E.2: Verification of anisotropy analysis algorithm for test case 2

## F. Examples of anisotropy curves for borehole 3-5

Fig. F.1: Anisotropy curve for joint 9-1 upper profile

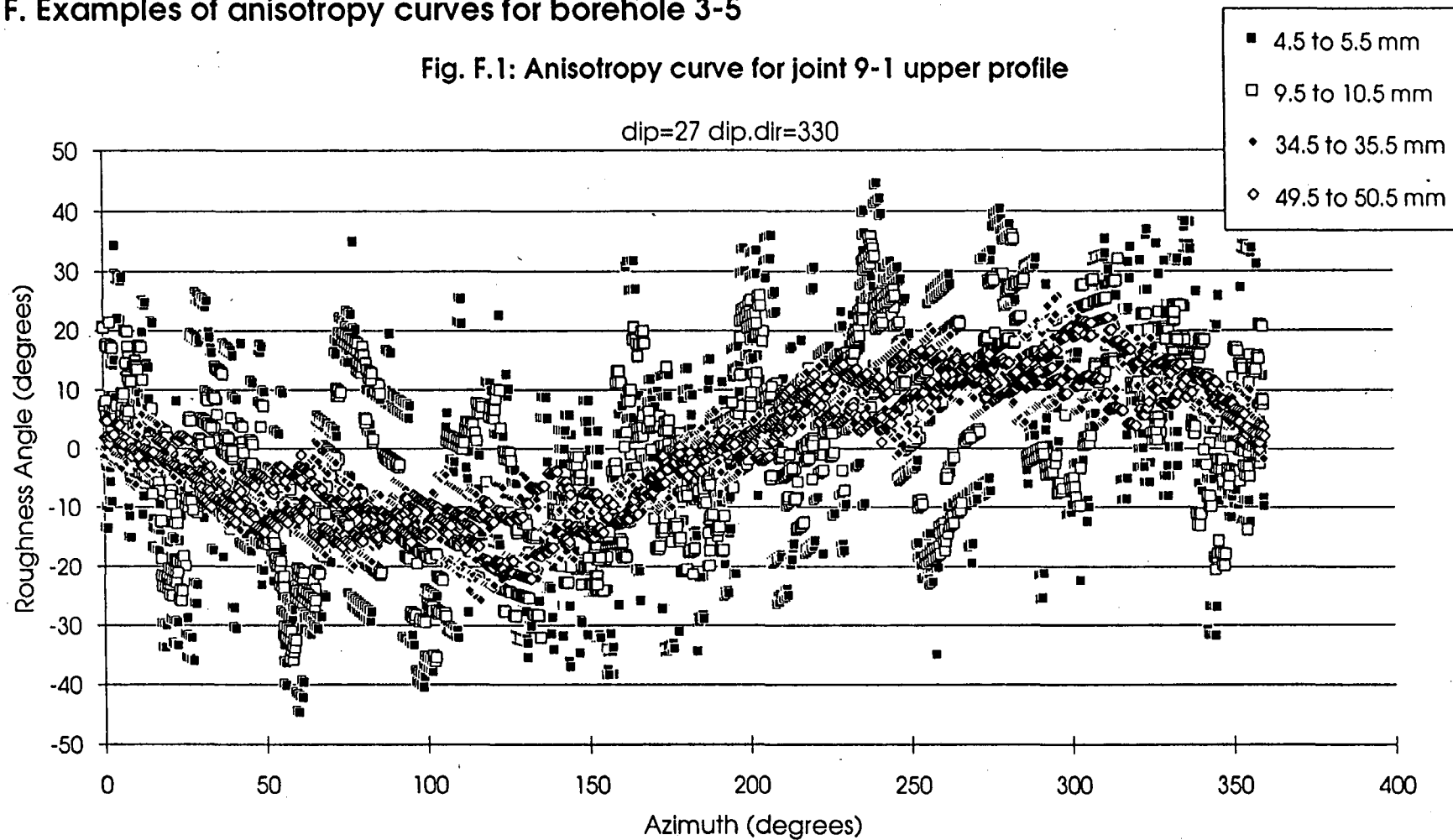


Fig. F.2: Anisotropy curve for joint 9-1 lower profile

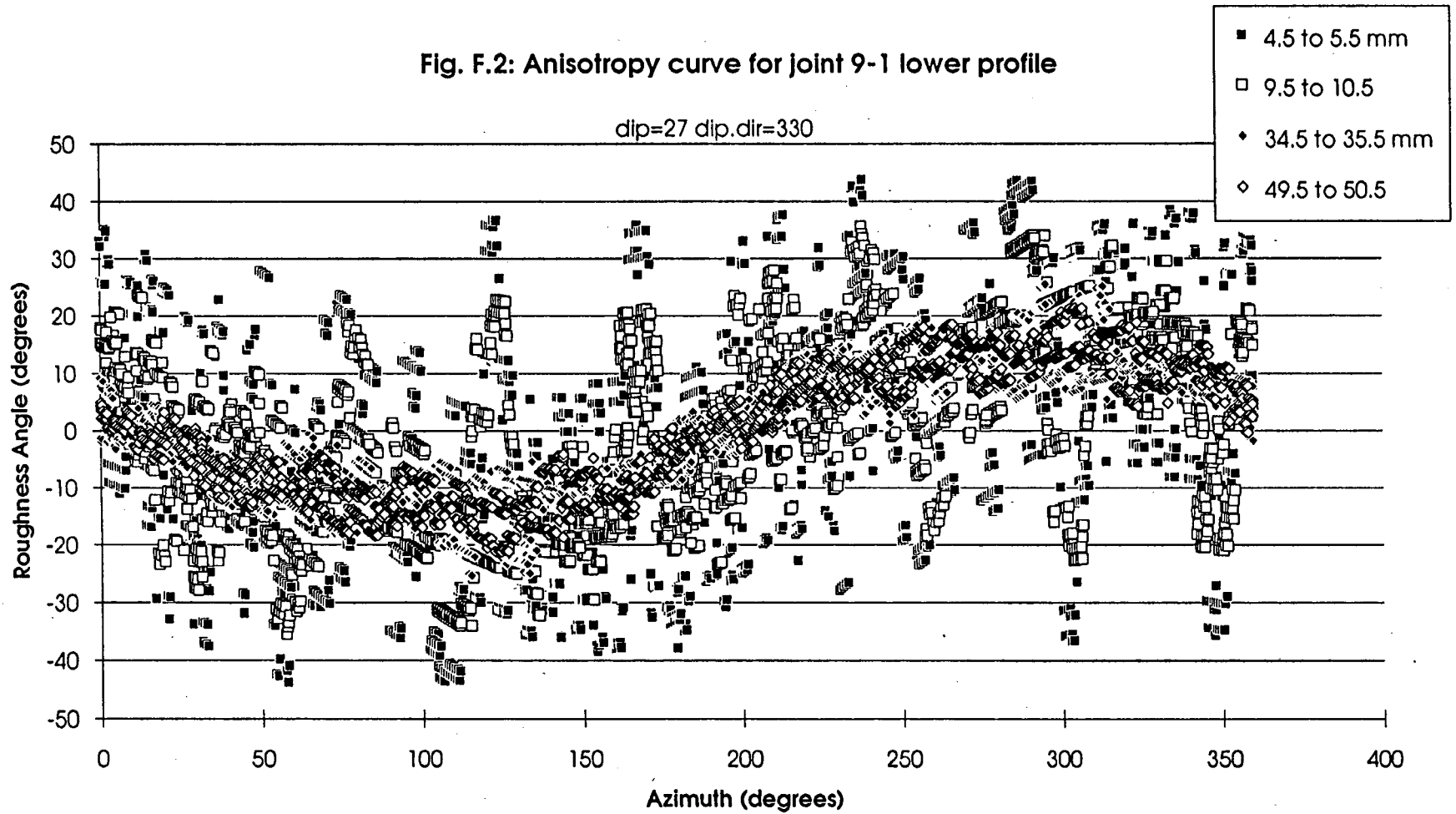


Fig. F.3: Anisotropy curve for joint 10-2 upper profile

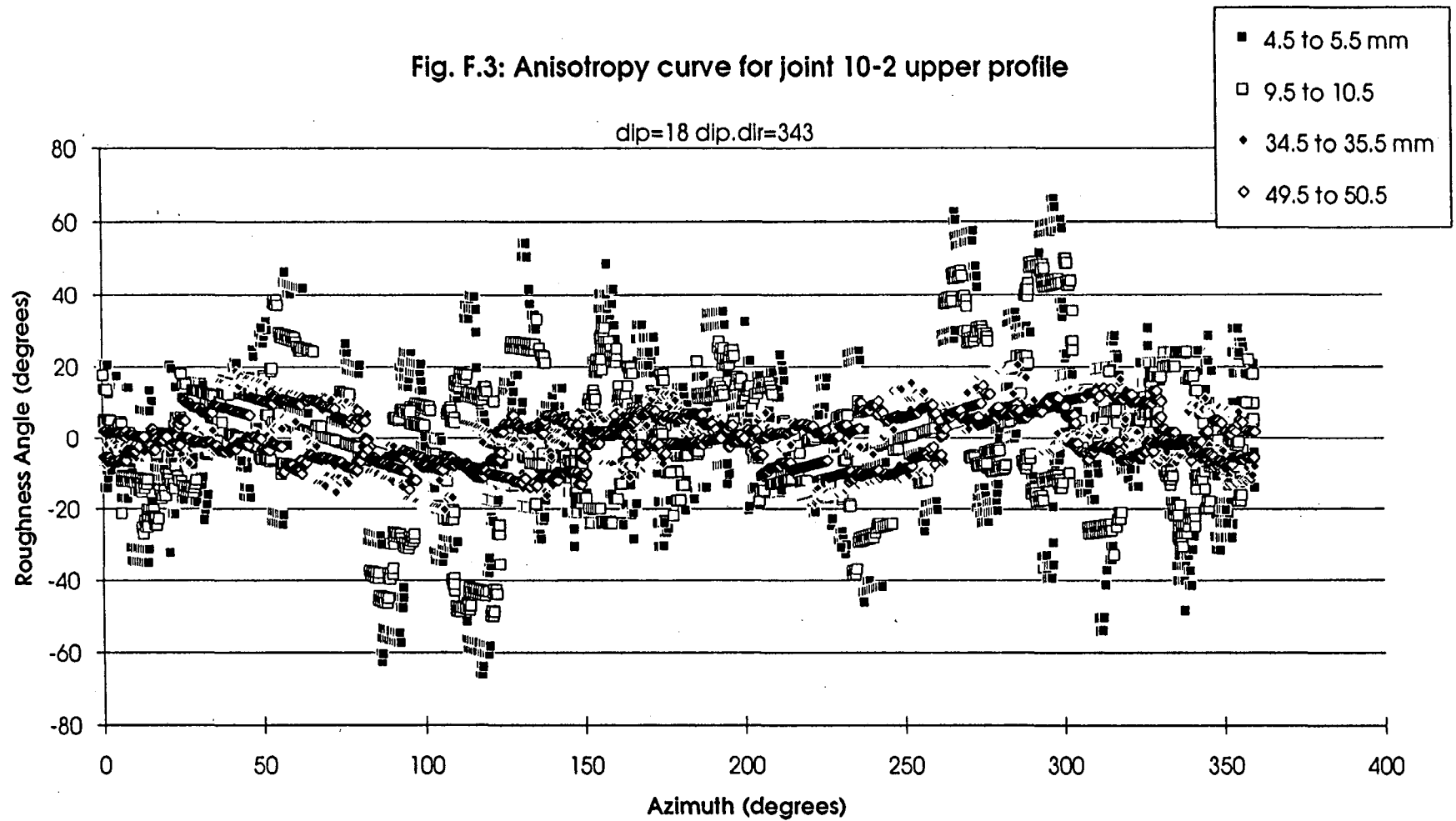




Fig. F.4: Anisotropy curve for joint 10-2 lower profile

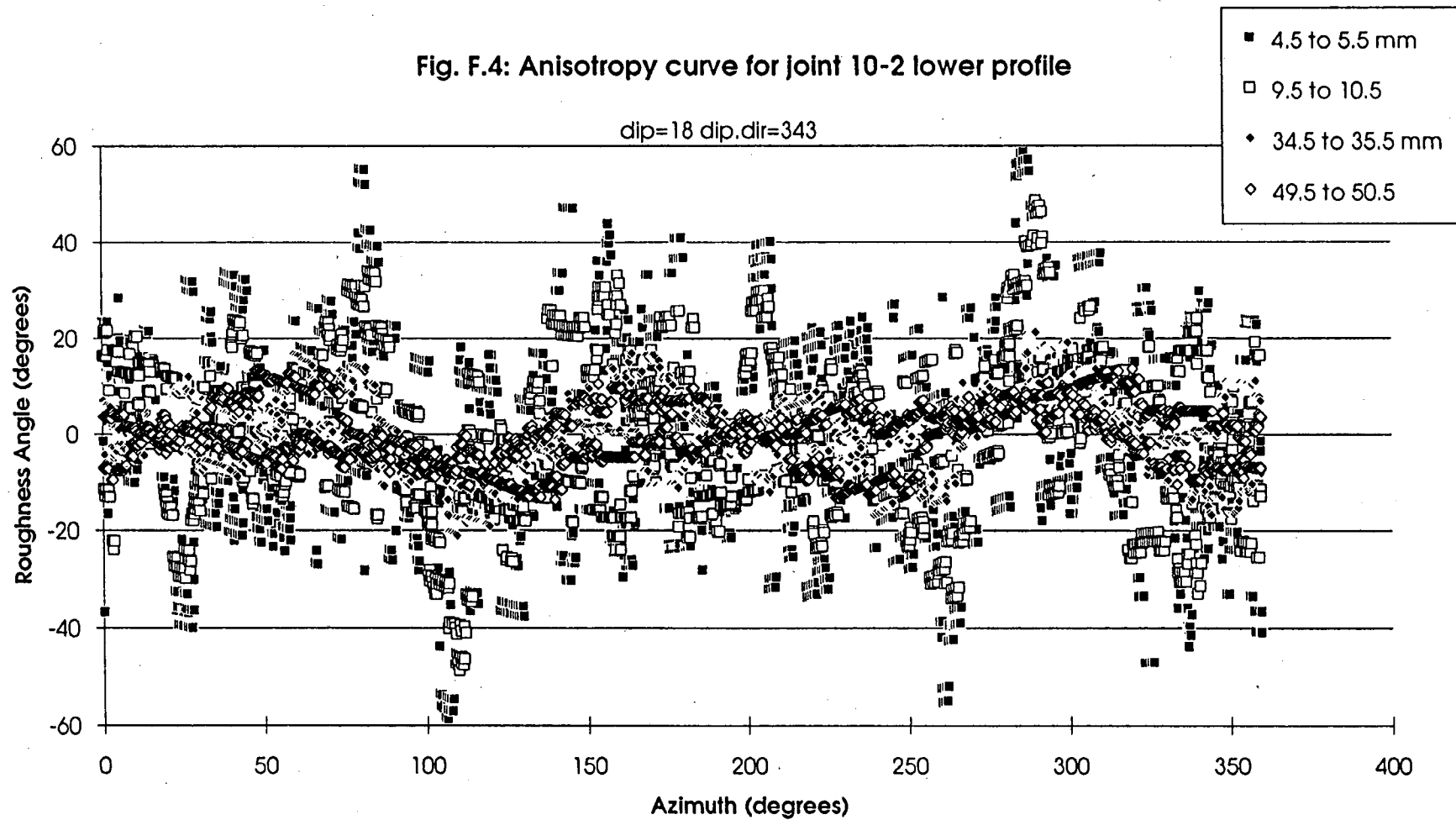


Fig. F.5: Anisotropy curve for joint 10-3 upper profile

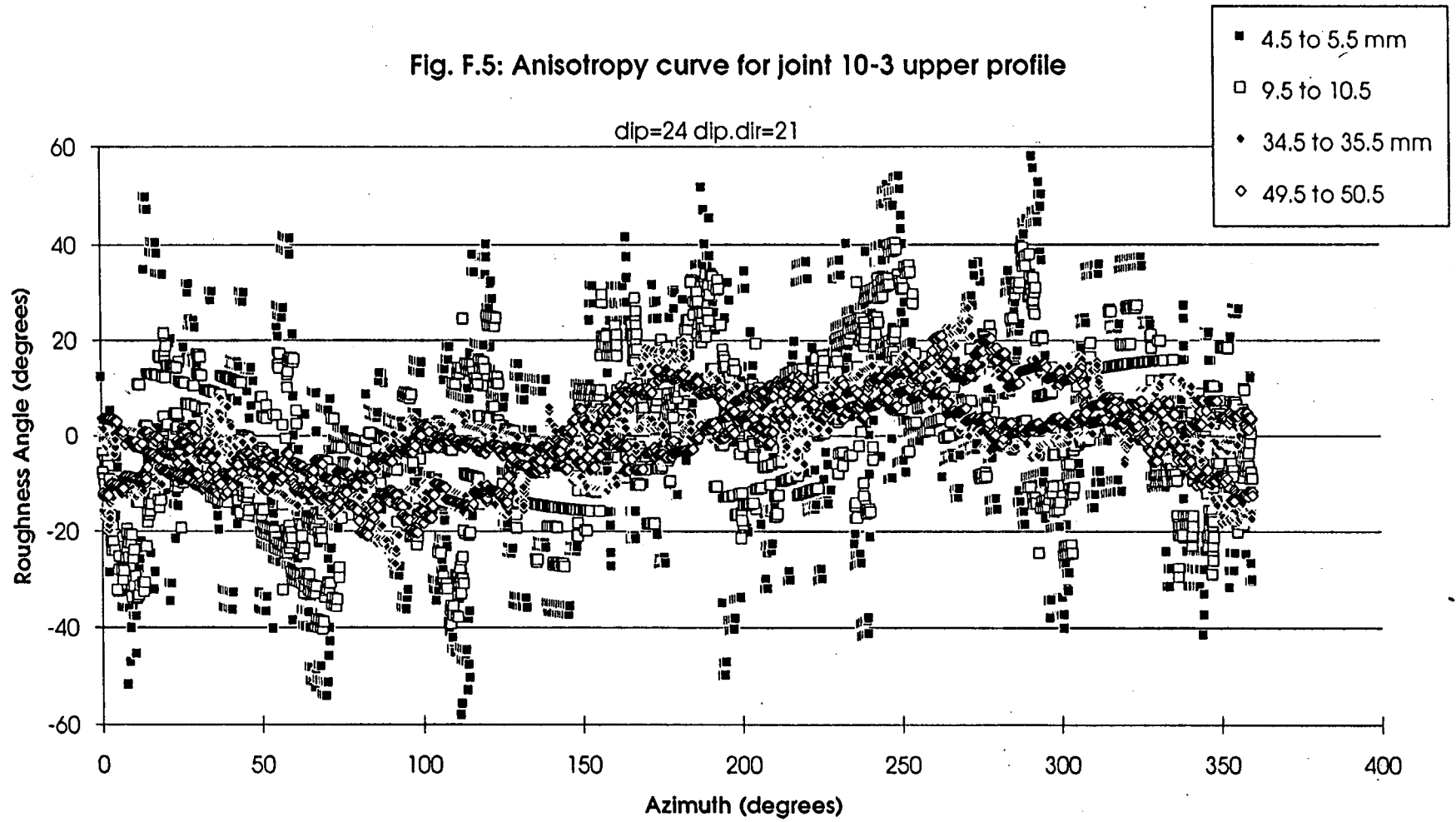


Fig. F.6: Anisotropy curve for joint 10-3 lower profile

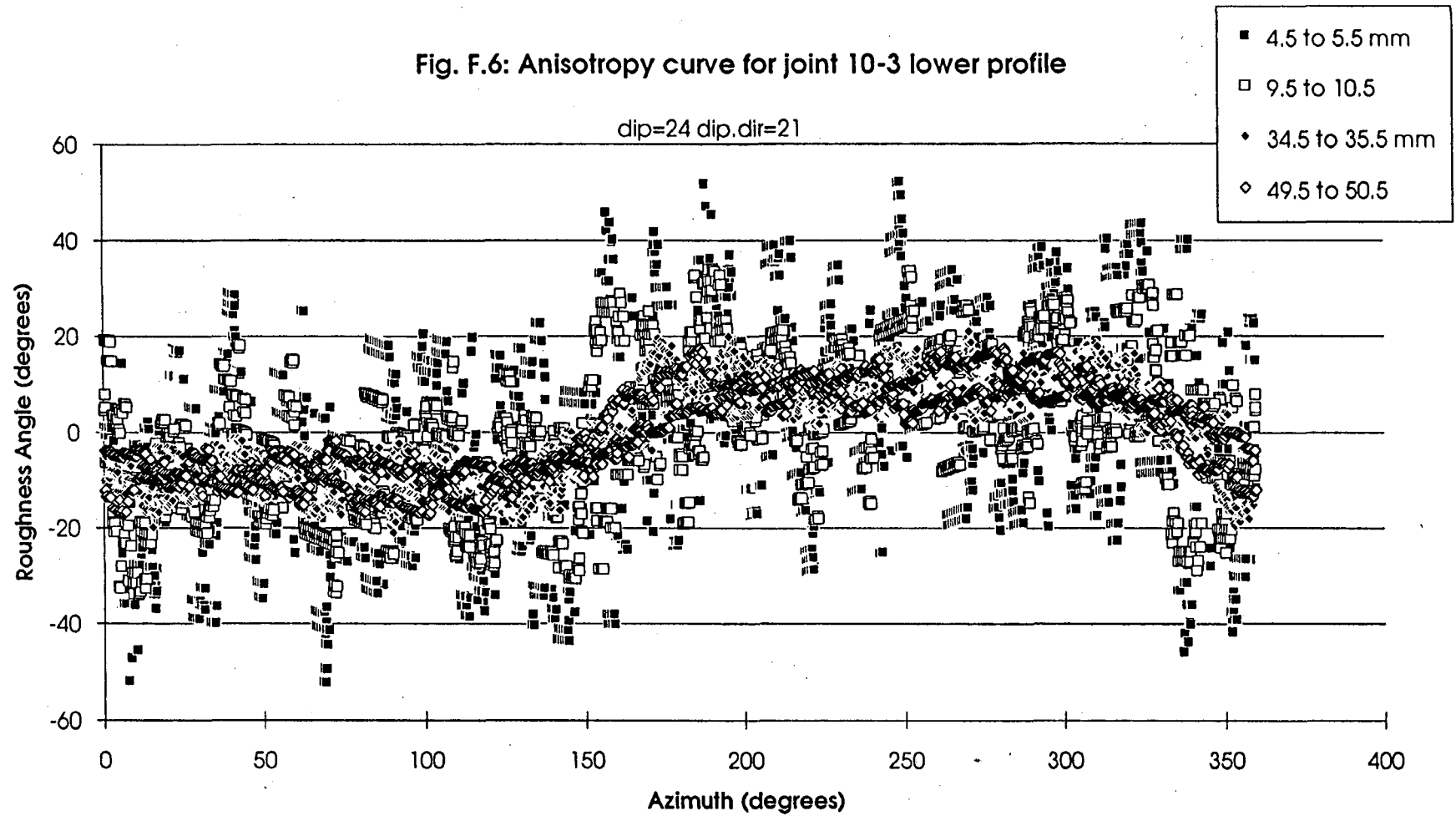


Fig. F.7: Anisotropy curve for joint 10-4 upper profile

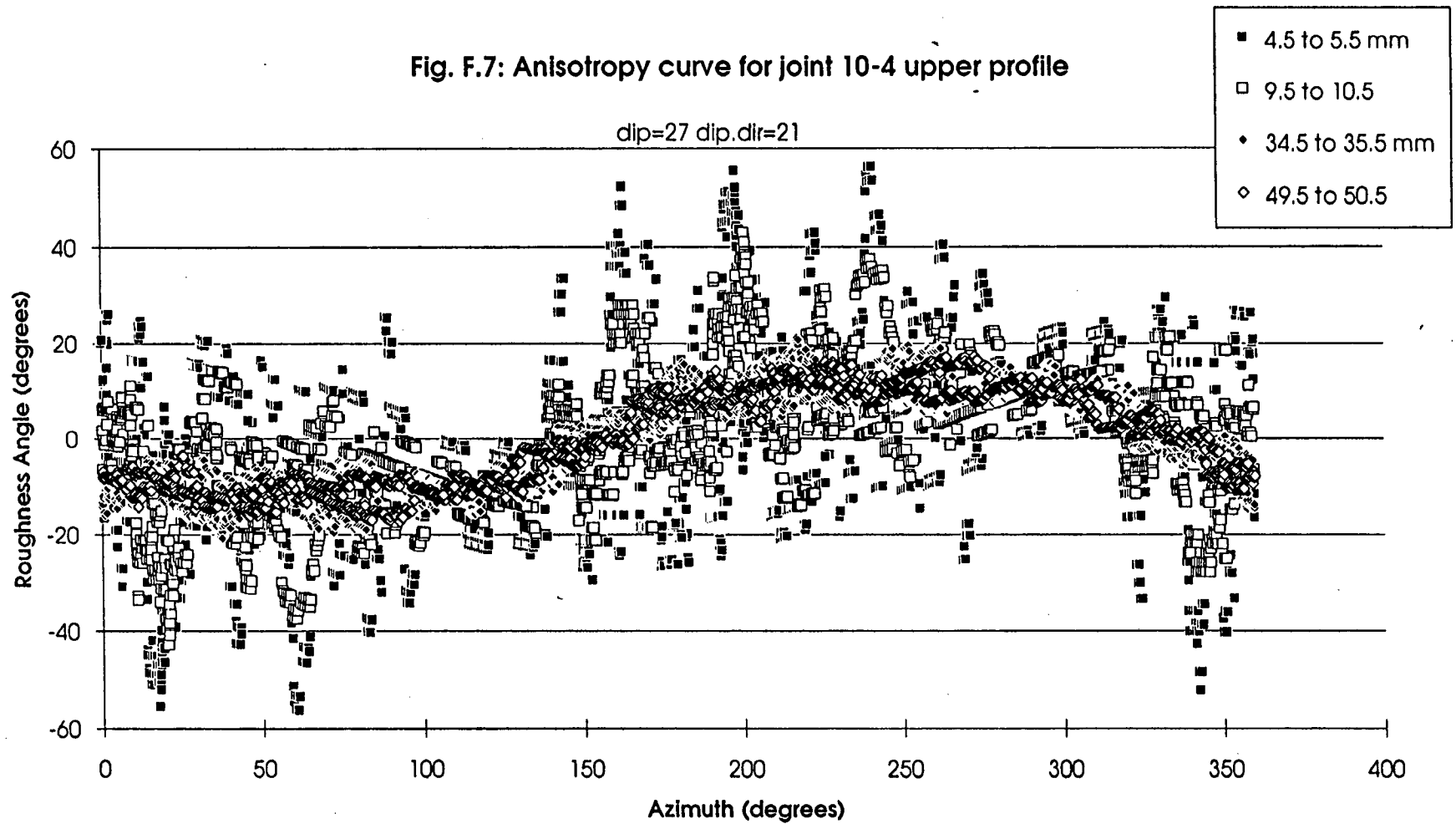


Fig. F.8: Anisotropy curve for joint 10-4 lower profile

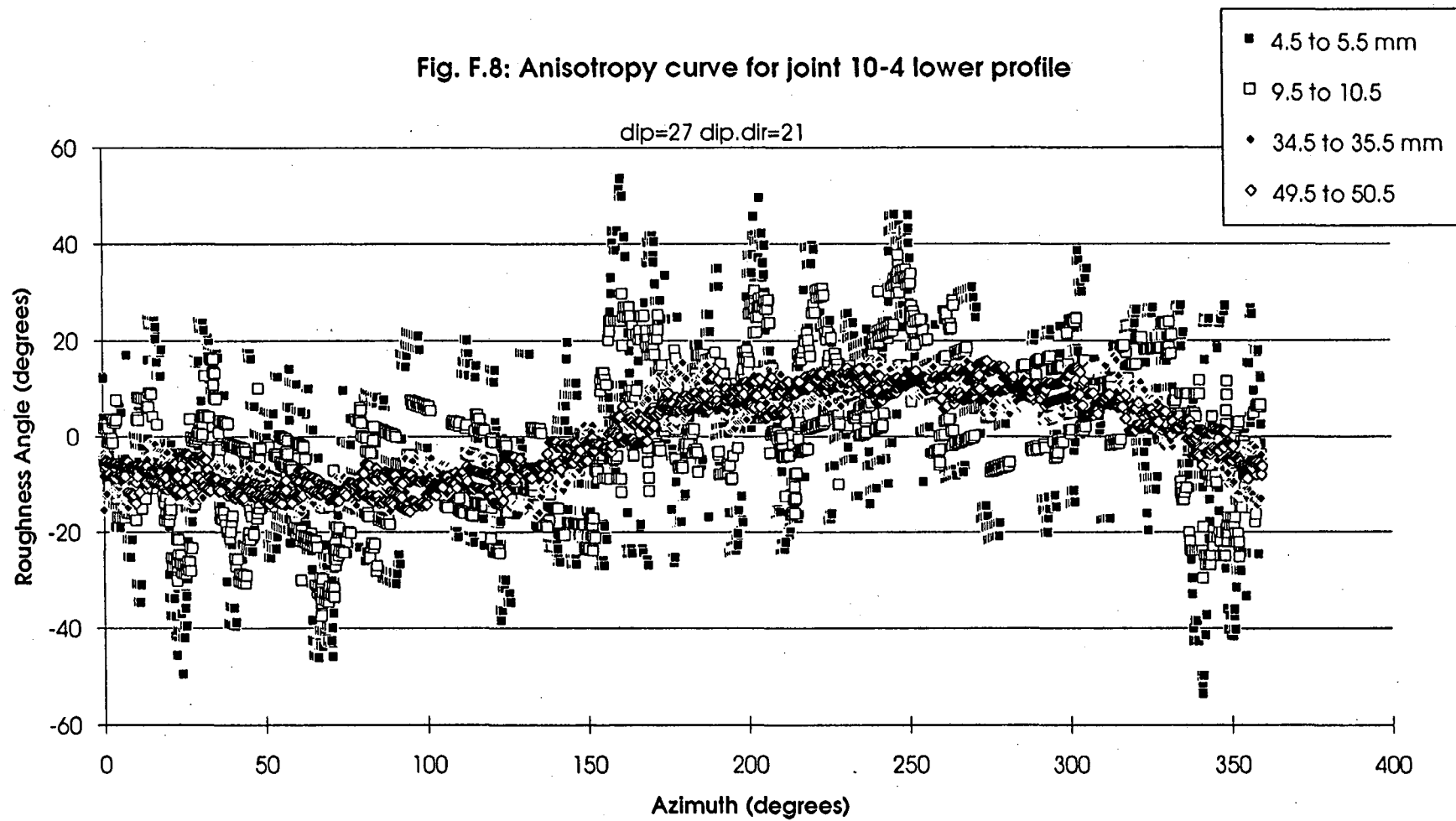


Fig. F.9: Anisotropy curve for upper profile of joint 19-1

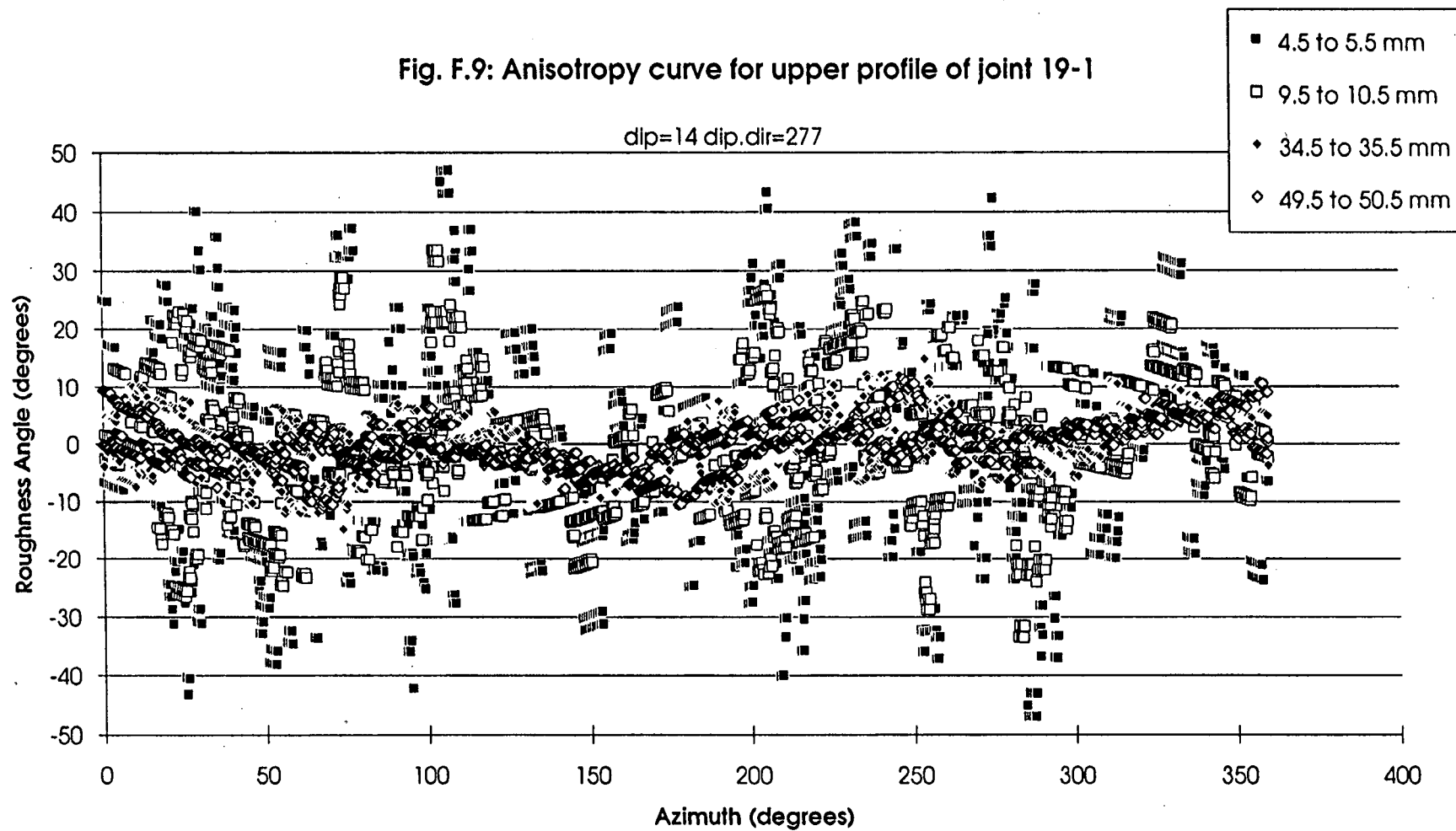
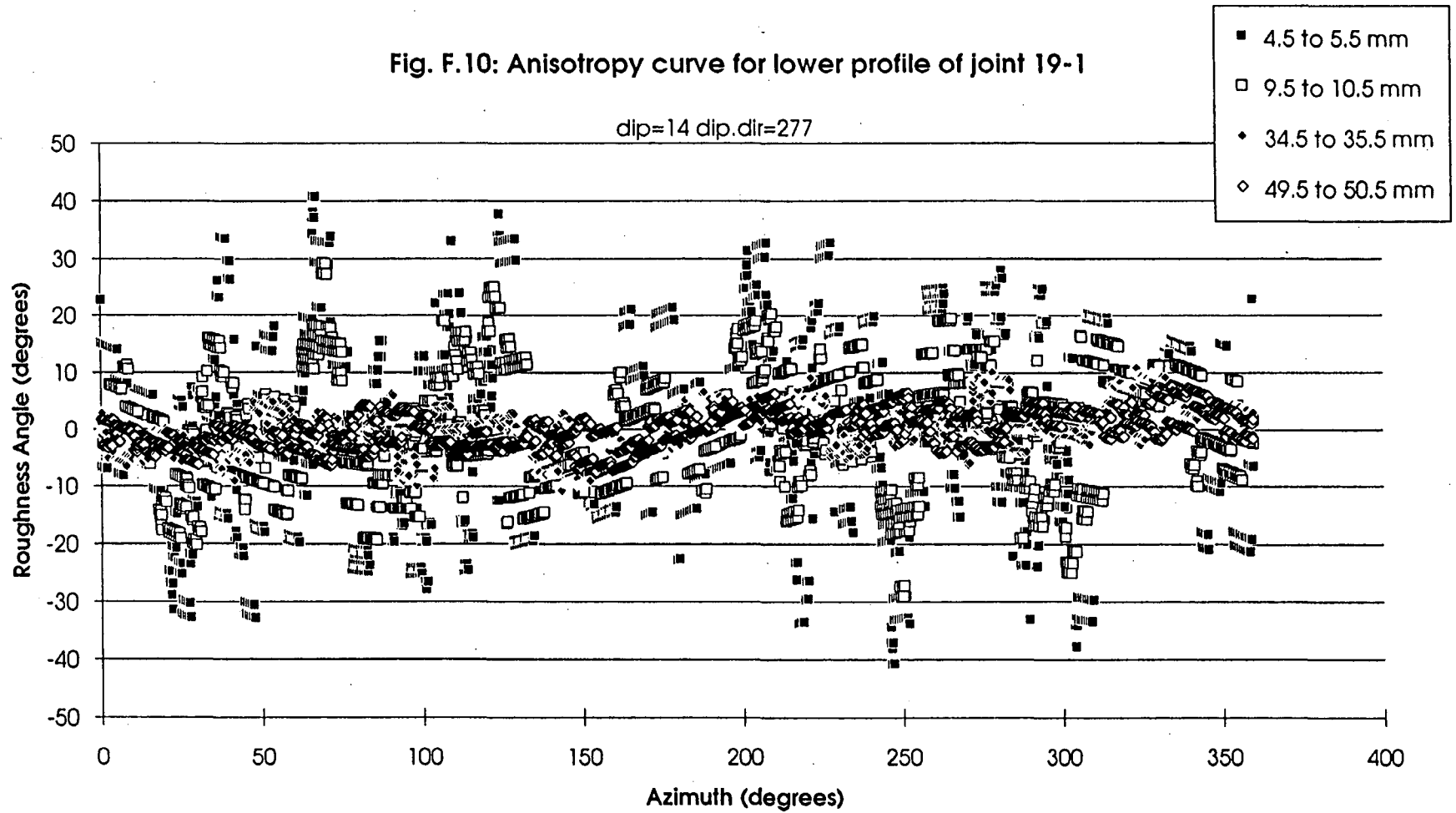


Fig. F.10: Anisotropy curve for lower profile of joint 19-1



### G. Results from aperture measurement synthetic experiment

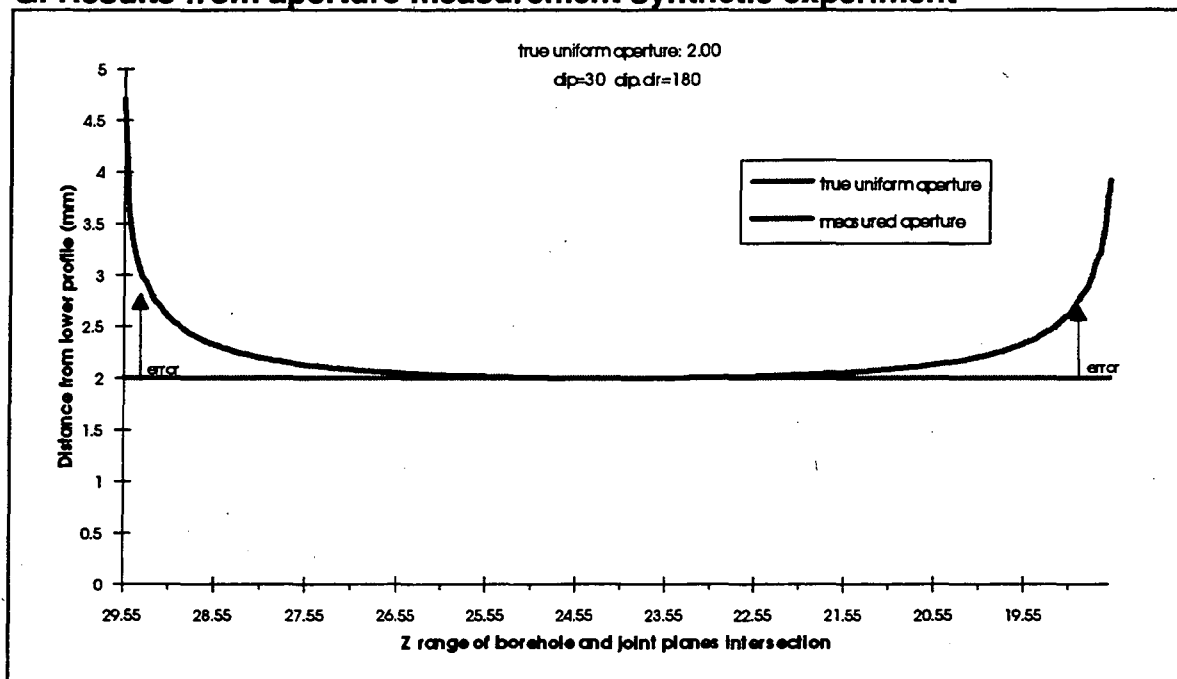


Figure G.1: Results of synthetic aperture measurement experiment for 30° dip

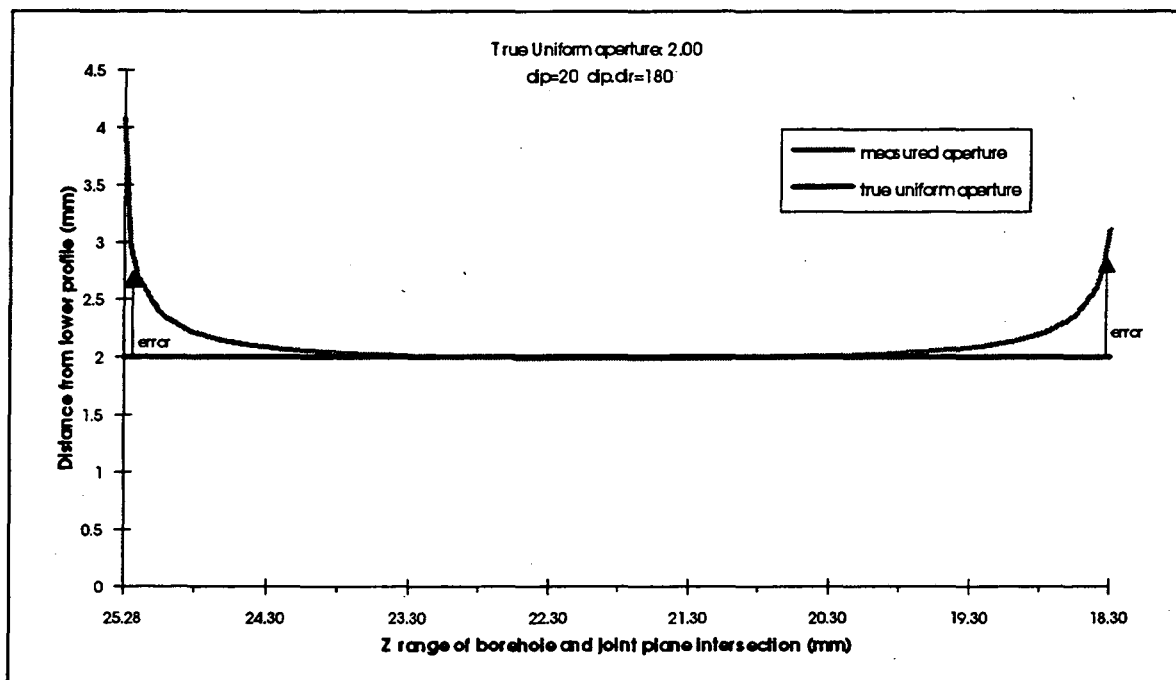


Figure G.2: Results of synthetic aperture measurement experiment for 20° dip



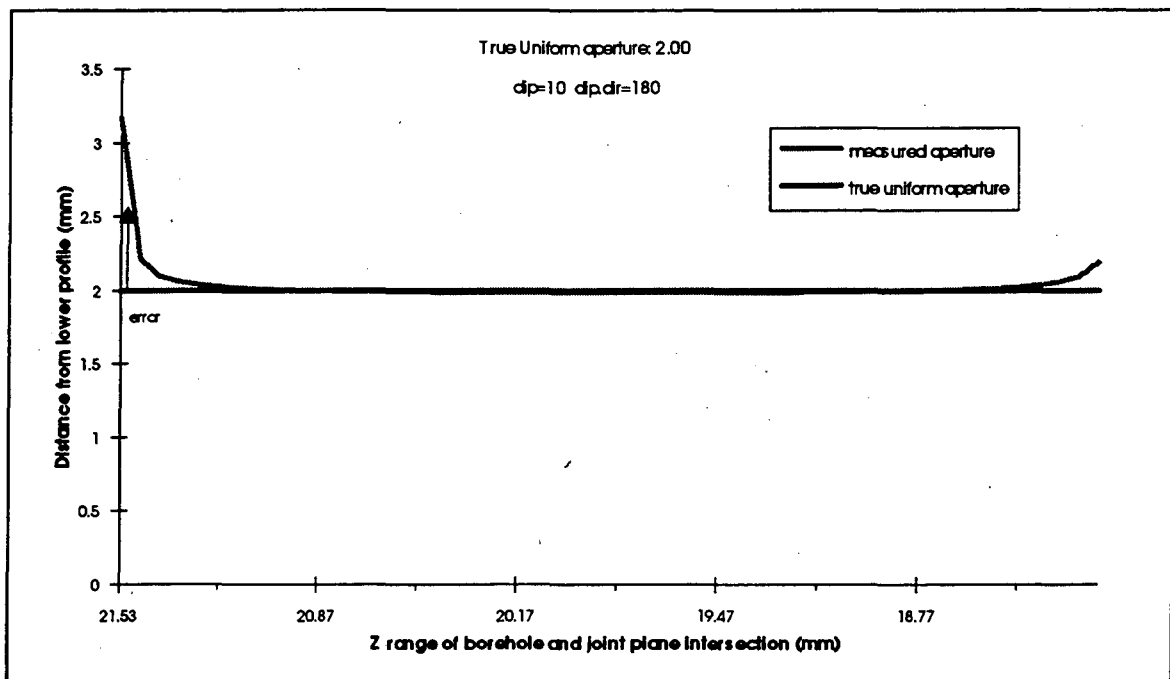


Figure G.3: Results of synthetic aperture measurement experiment for 10° dip

## H. Verification of unrolling algorithm

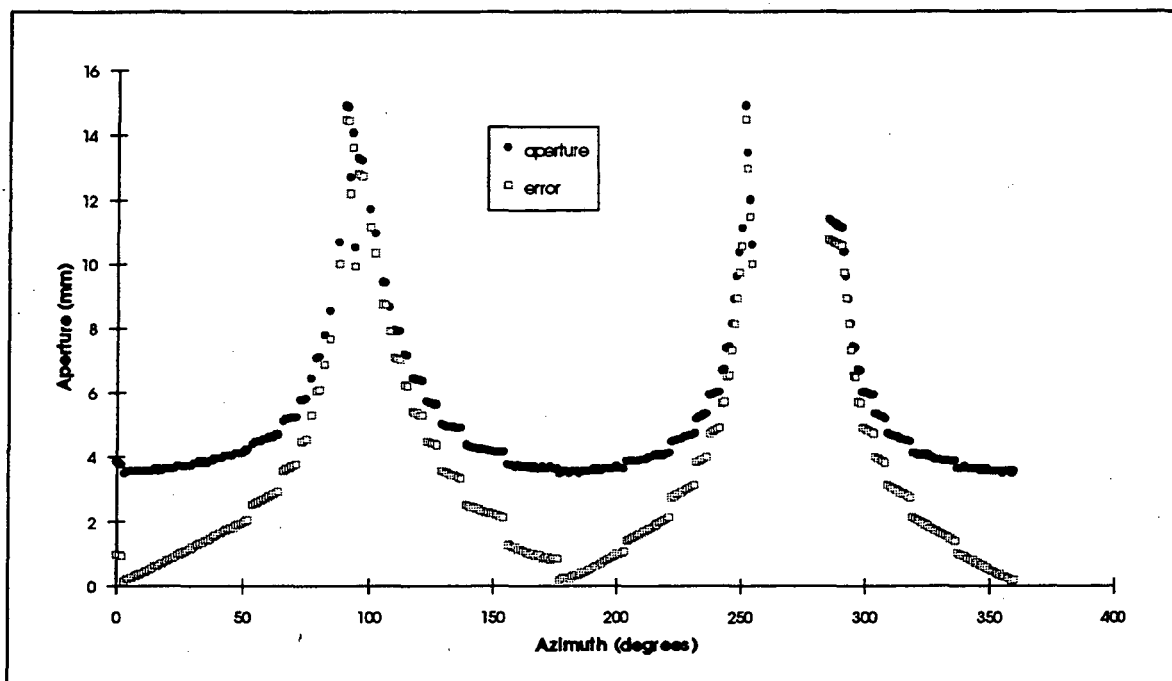


Figure H.1: Apertures of test data for verification of unrolling algorithm

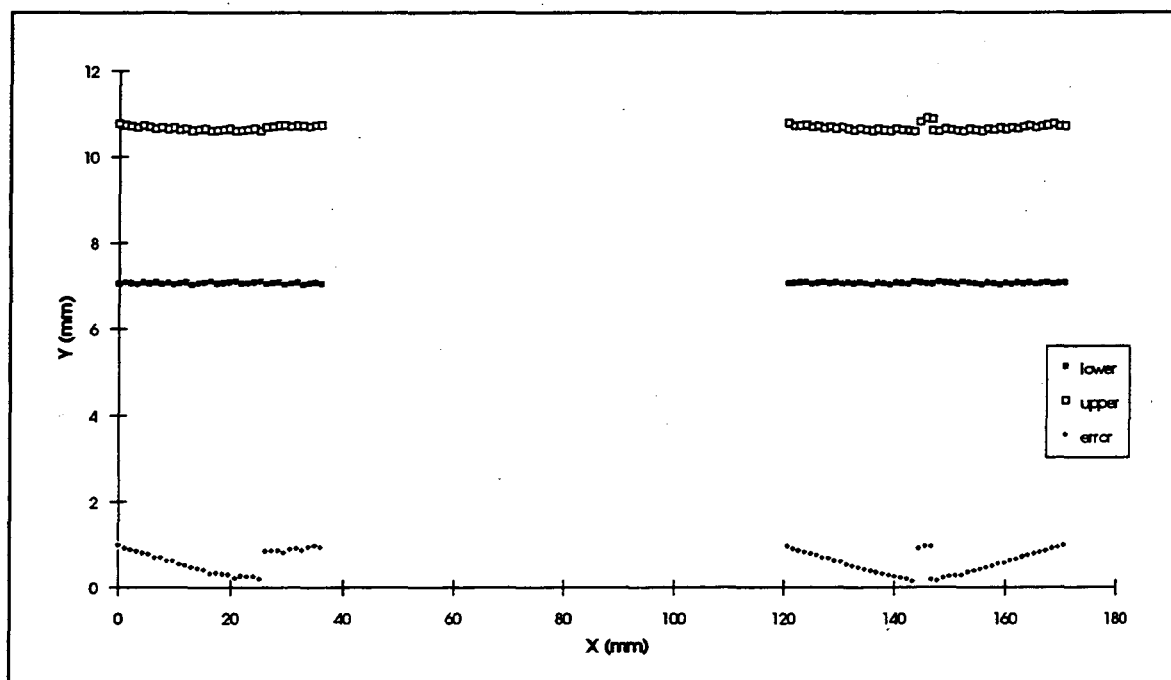


Figure H.2: Opposing profiles of test data for verification of unrolling algorithm

### I. Examples of aperture measurements on joints in borehole 3-5

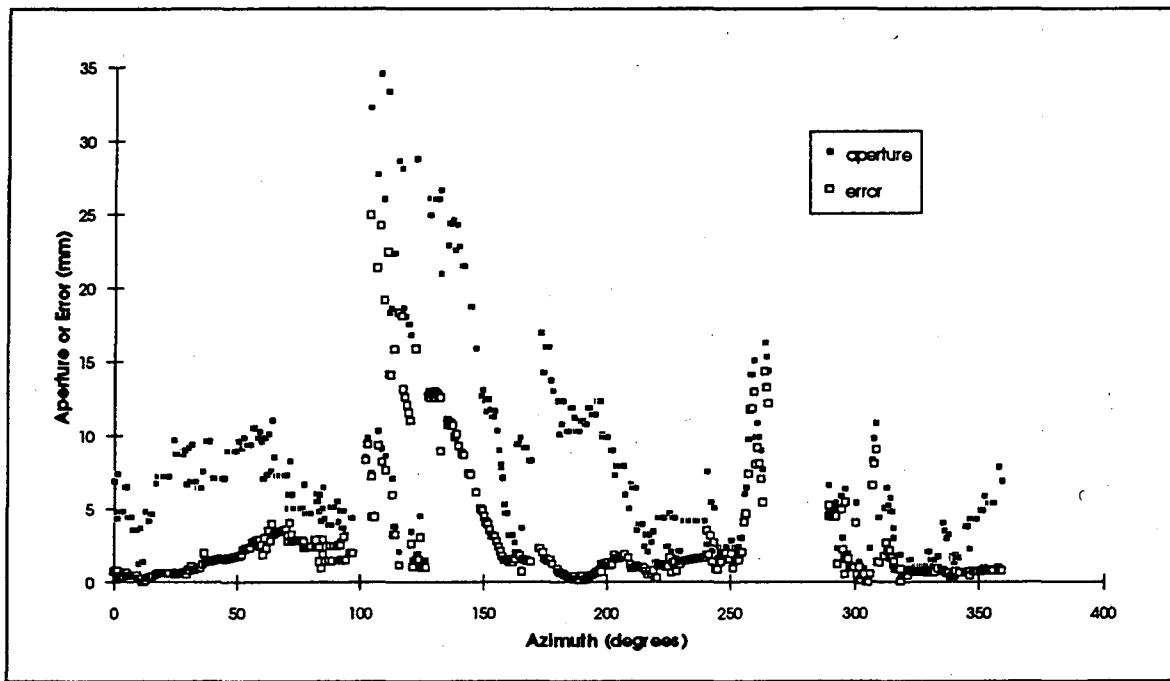


Figure I.1: Apertures and measurement errors for joint 18-1

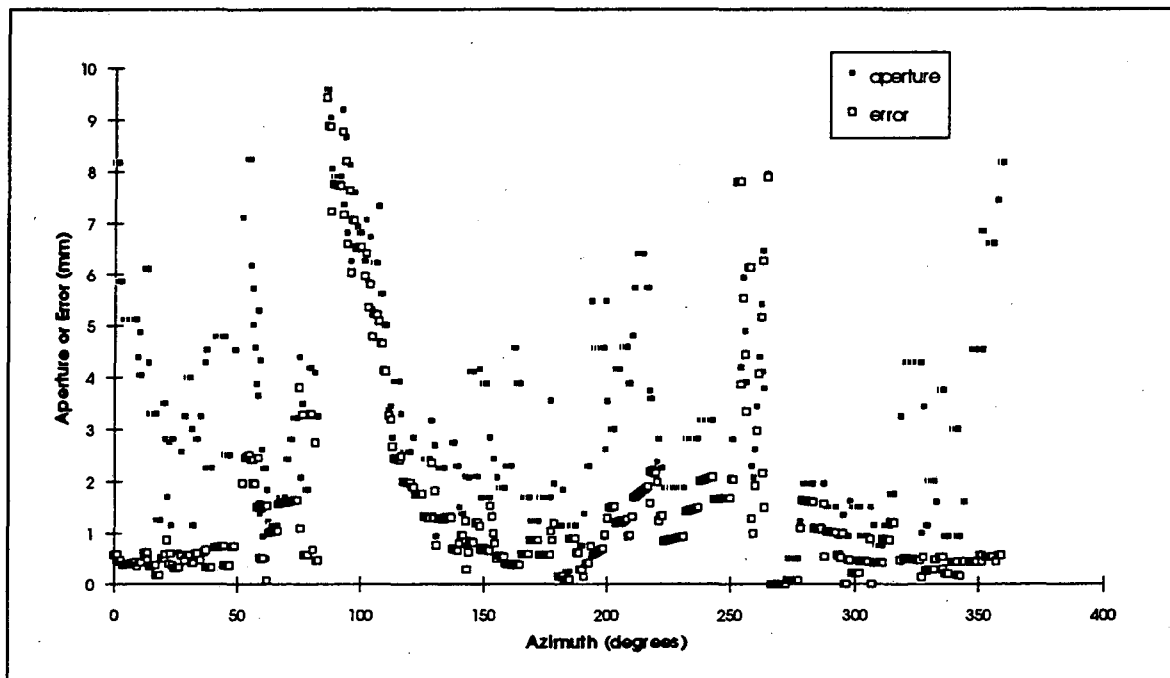


Figure I.2: Apertures and measurement errors for joint 19-2

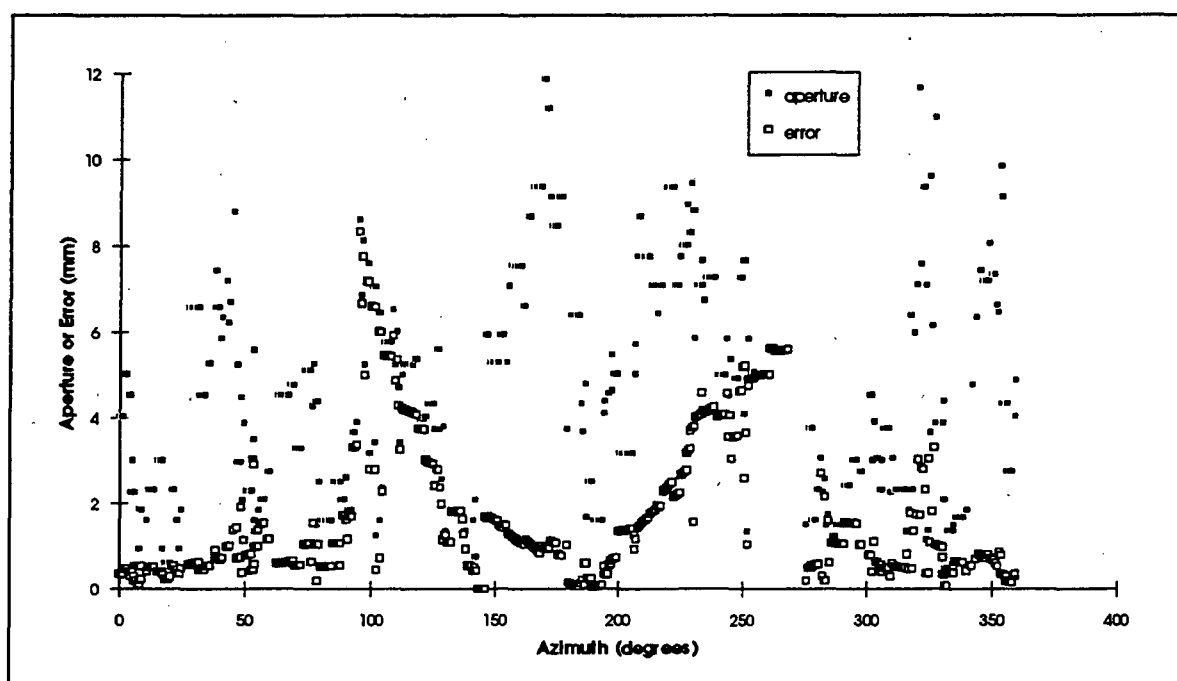


Figure I.3: Apertures and measurement errors for joint 19-3

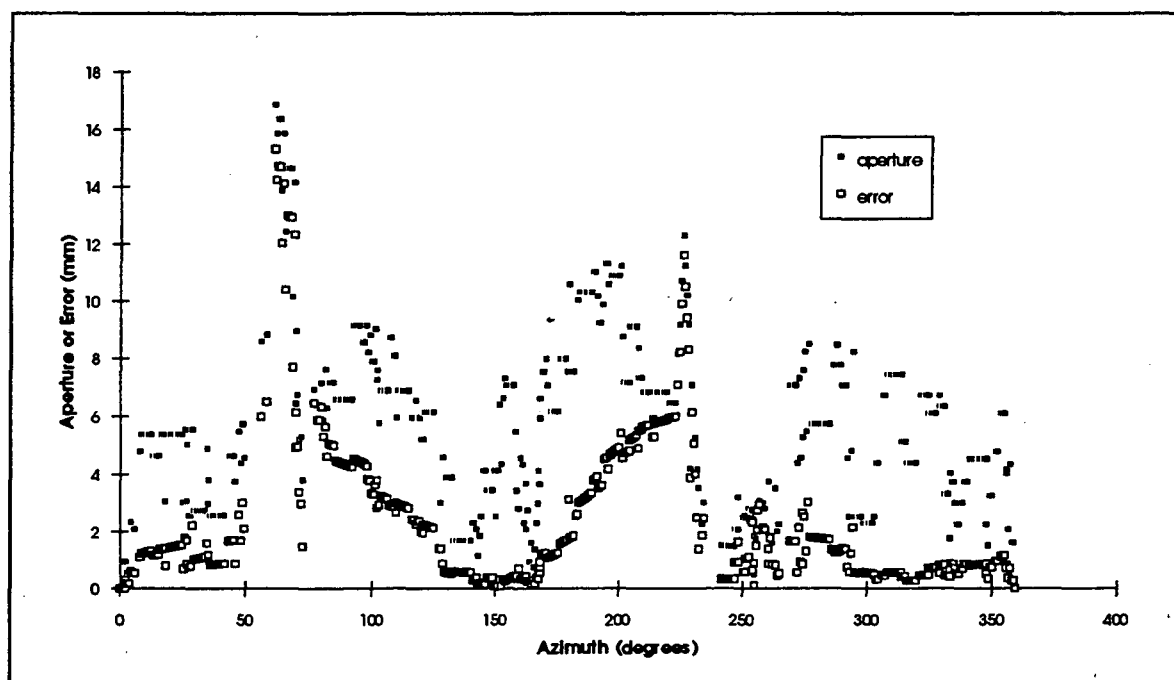


Figure I.4: Apertures and measurement errors for joint 19-4

## J. Examples of unrolled profiles from joints in borehole 3-5

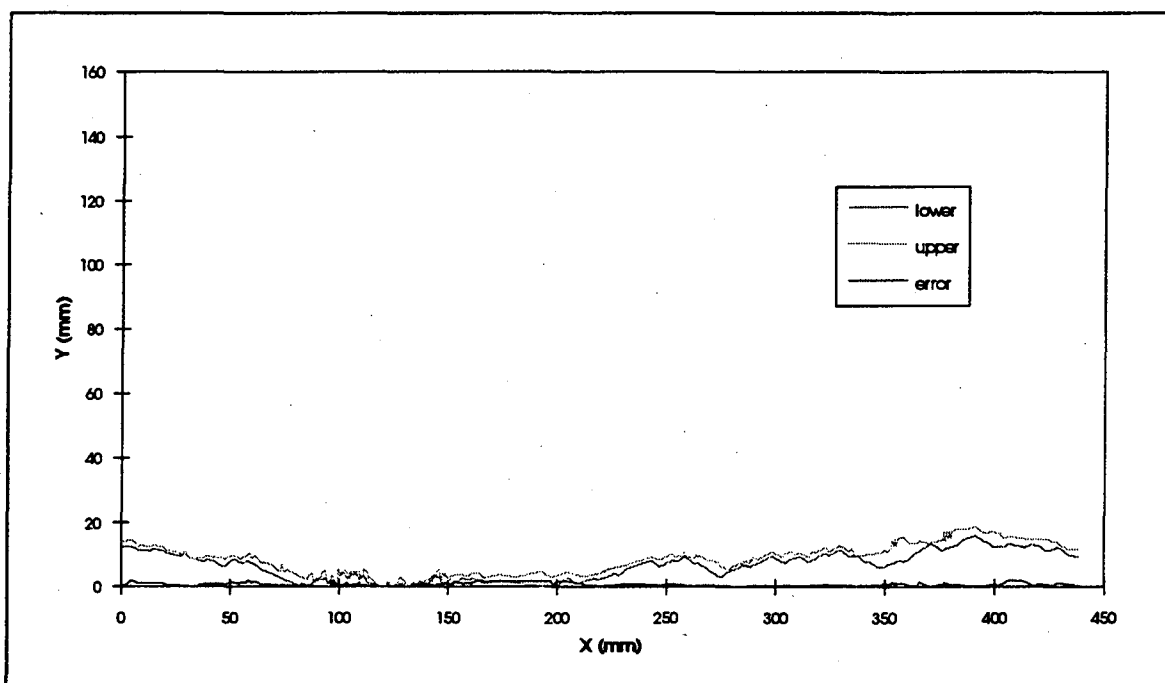


Figure J.1: Unrolled opposing profiles of joint 20-1

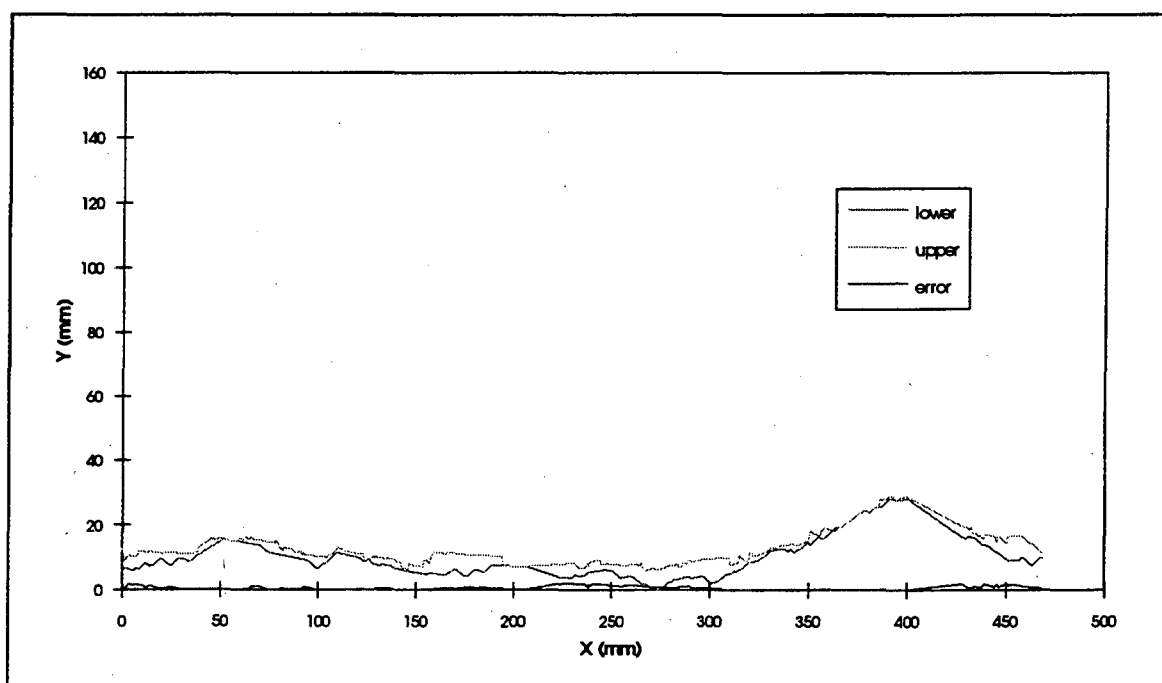


Figure J.2: Unrolled opposing profiles of joint 20-2

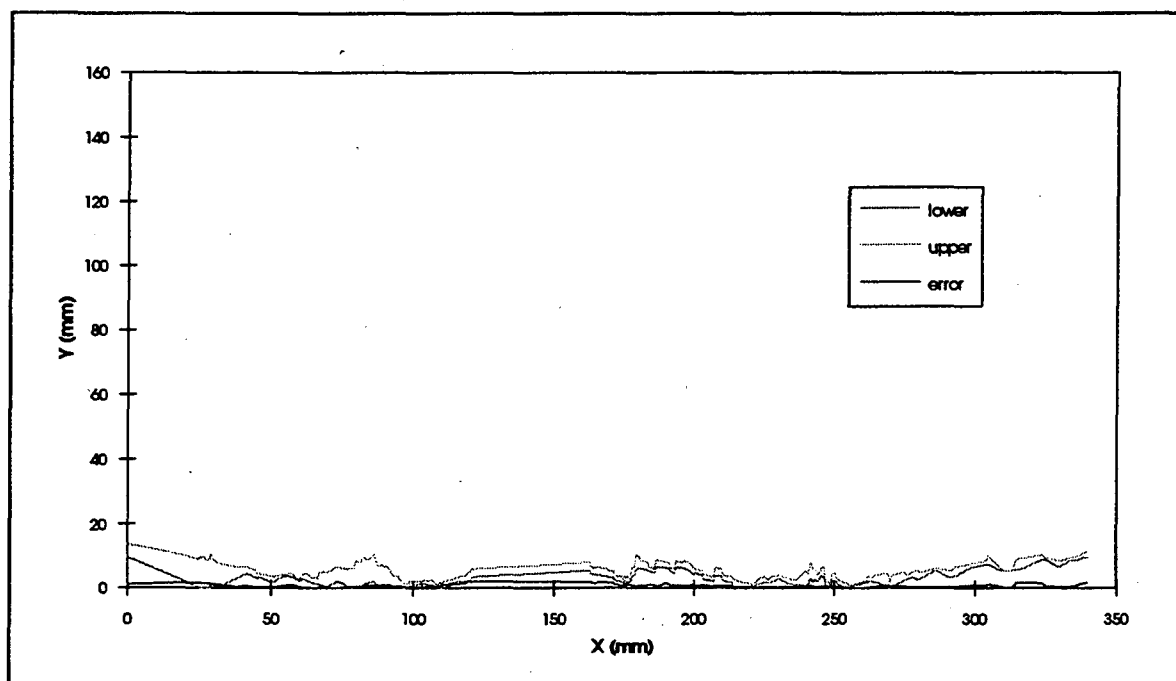


Figure J.3: Unrolled opposing profiles of joint 20-3

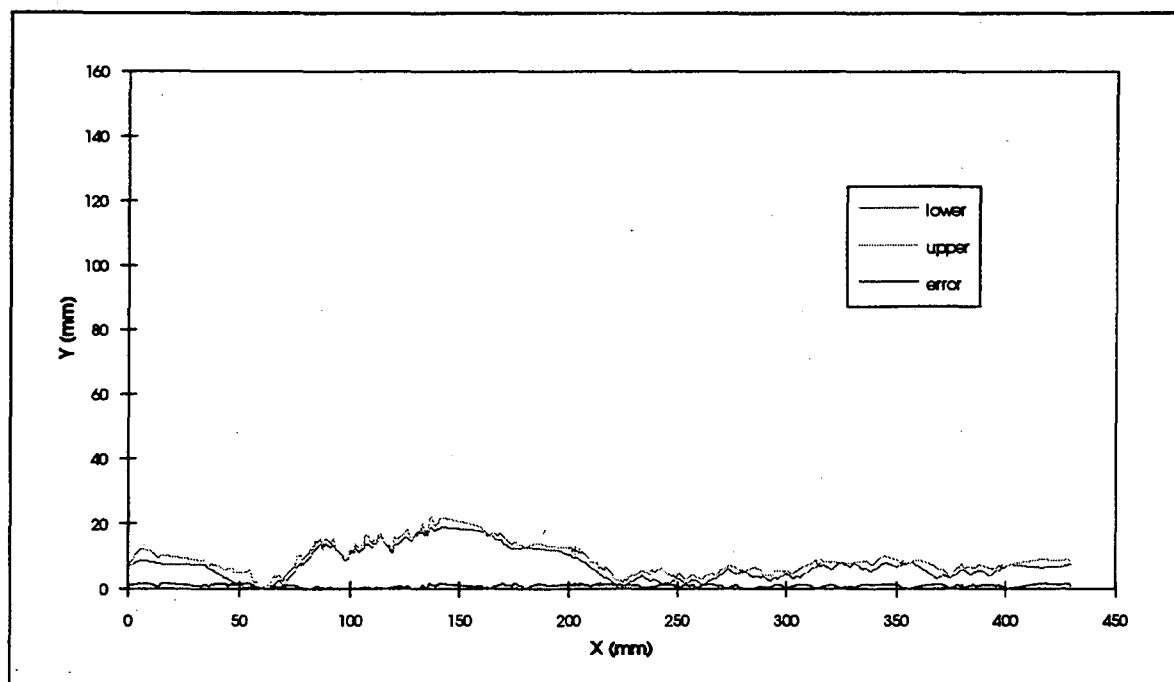


Figure J.4: Unrolled opposing profiles of joint 21-1

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