Beach changes from construction of San Onofre Nuclear Generating Station, 1964-1989

By

Reinhard E. Flick
California Department of Boating and Waterways
Scripps Institution of Oceanography
La Jolla, CA

Jerome R. Wanetick
Scripps Institution of Oceanography

M. Hany S. Elwany
Coastal Environments
and Scripps Institution of Oceanography

Robert S. Grove
Southern California Edison Company
Rosemead, CA

B. Walton Waldorf
Oregon State University
Corvallis, OR

ABSTRACT

Construction of the San Onofre Nuclear Generating Station (SONGS) on the coast at Camp Pendleton in northern San Diego County, CA, between 1964 and 1984 provides a unique opportunity to document a full cycle of long-term widening of a naturally narrow beach due to structures and sand fill, and the return to a narrow condition following cessation of fill placement and removal of the structures. Beach changes documented from 1964 to 1989 illustrate and confirm that the combination of sand fill and sand retention structures will widen a beach in southern California beyond its natural width essentially indefinitely. Furthermore, if the upcoast beach is sufficiently wide for longshore transport to bypass the structures, this is accomplished with no detrimental down-coast effects on beach width. Survey data suggest that nourishment sand near SONGS remained nearby, moving offshore rather than rapidly and noticeably alongshore as expected.

ADDITIONAL KEYWORDS: Nourishment, sand retention, coastal structures, San Onofre, coastal construction, beach monitoring.

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The San Onofre Nuclear Generating Station (SONGS) is located near the northern extent of the Oceanside littoral cell as shown in Figure 1. A littoral cell is defined as an isolated geographical compartment, usually bounded by headlands, that contains a complete cycle of sand sources, transport paths, and sinks (Inman and Frautschy 1965). The Oceanside cell is bounded on the north by Dana Point and on the south by Point La Jolla and the Scripps-La Jolla submarine canyons.

Historically, the major sources of sand for the cell have been the ephemeral rivers and streams and erosion of the Miocene cliffs that back most of the reach (Flick and Elwany 2006). Both these sources are most important during episodically occurring wet, stormy winters (Kuhn and Shepard 1984; Simon, Li and Assoc. 1988; Young *et al*. 2009) but landsliding can also contribute substantial amounts of cliff material in the San Onofre region. Cliff erosion can occur either because of uncontrolled surface runoff, which causes gullying (Kuhn *et al.* 1980) or because of direct wave attack at the base. Wave induced cliff undermining and collapse is most serious when the beaches are narrow and unable to provide a wave dissipating buffer (Young *et al*. 2009).

Waves generated by storms in the Pacific Ocean are the most important factor in transporting sand on-offshore and longshore in southern California. The Southern California Bight is a complicated region for wave processes since the coastal orientation and offshore islands greatly affect the wave exposure. The islands and associated shoals both shelter the coast by blocking wave energy and refract the wave trains that pass through the gaps (Pawka *et al*. 1984). Wave exposure in the bight is a strong function of location and of deepwater wave approach angle. San Onofre is highly sheltered from the west by Santa Catalina and San Nicholas islands, and from the northwest by Santa Cruz, Santa Rosa and San Miguel islands. In contrast, San Onofre is relatively exposed to the southwest.

Seasonal changes in width associated with seasonal variations in wave energy have been extensively documented on southern California beaches (Aubrey *et al*. 1980, Thompson 1987, Yates *et al*. 2009a). Seasonally changing wave exposure also tends to reverse the longshore transport of sand. At San Onofre, this tendency may be pronounced, with generally southward transport during winter and northward transport during summer. Limited directional wave measurements made during 1985-1986 (Schroeter *et al*. 1989) show a close balance between southward and northward transport rates, implying little net transport over at least this two-year period. Long term, net transport is to the south. This is strongly suggested by the build-up of littoral sand on the northern, upcoast side of temporary barriers such as the laydown pads.

Construction of SONGS from 1964 to 1984 has provided extensive opportunity to study beach and inner shelf physical and biological processes (e.g. California Coastal Commission 2009). Long-term coastal monitoring programs at SONGS were institutionalized by the permitting agencies in order to maintain water quality, species numbers and diversity, and shoreline stability. The California Coastal Commission and the San Diego Regional Water Quality Control Board played key roles in mandating and supervising these programs, which were sponsored by Southern California Edison (SCE), but managed by the independent Marine Review Committee (MRC) during and following construction of SONGS Units 2 and 3 starting around 1974. Eventual mitigation requirements included restoration of a lagoon, chosen to be San Dieguito lying between the cities of Solana Beach and Del Mar, CA (California Coastal Commission 2005), and construction of a kelp reef off San Clemente (Elwany *et al*. 2010).

Sheet-pile that formed construction-work area "laydown pads" was in place 1964-1966 for SONGS Unit 1, and again 1974-1984 for Units 2 and 3. Approximately 1 million cubic yards of fill came from cliff excavation and underwater trenching for the 5.5 m diameter SONGS cooling system pipes. Unusual flooding in the winters of 1978, 1980, and 1982 also contributed substantial quantities of river sand to the area. Beach monitoring was done using photographs and beach profile elevation surveys until naturally-narrow beach conditions returned some years after the removal of the Units 2 and 3 laydown pad in 1985.

The laydown pads, especially the long-lived pad in existence from 1974 to 1984 used for construction of Units 2 and 3, trapped the deposited sand and interrupted the longshore transport causing substantial widening of the local beaches, especially north of the plant. After removal of this pad, the sand trapped behind it bifurcated into two bulges that remained relatively close to the site for several years, consistent with directional wave observations. Relatively rapid retreat of the beach was observed directly in front of SONGS, and to a lesser degree to the north. Longshore and offshore wave-induced transport redistributed the sand and the beaches reverted to their relatively narrow, pre-1964 condition, just as was predicted in pre-construction studies.

This paper describes the extensive beach changes that resulted from the construction of laydown pads and from the large volume of beach sand contributed from cliff excavation and pipe-laying activities. It is shown that the added sand supply and the interruption of longshore transport by the laydown pads significantly widened the previously marginal San Onofre beaches. These changes were documented photographically. In turn, the removal of the Units 2 and 3 pad in early 1985 precipitated a local narrowing of the beaches adjacent to SONGS. This was documented by beach profile measurements carried out between May 1985 and September 1987 and by a final survey in January 1989.

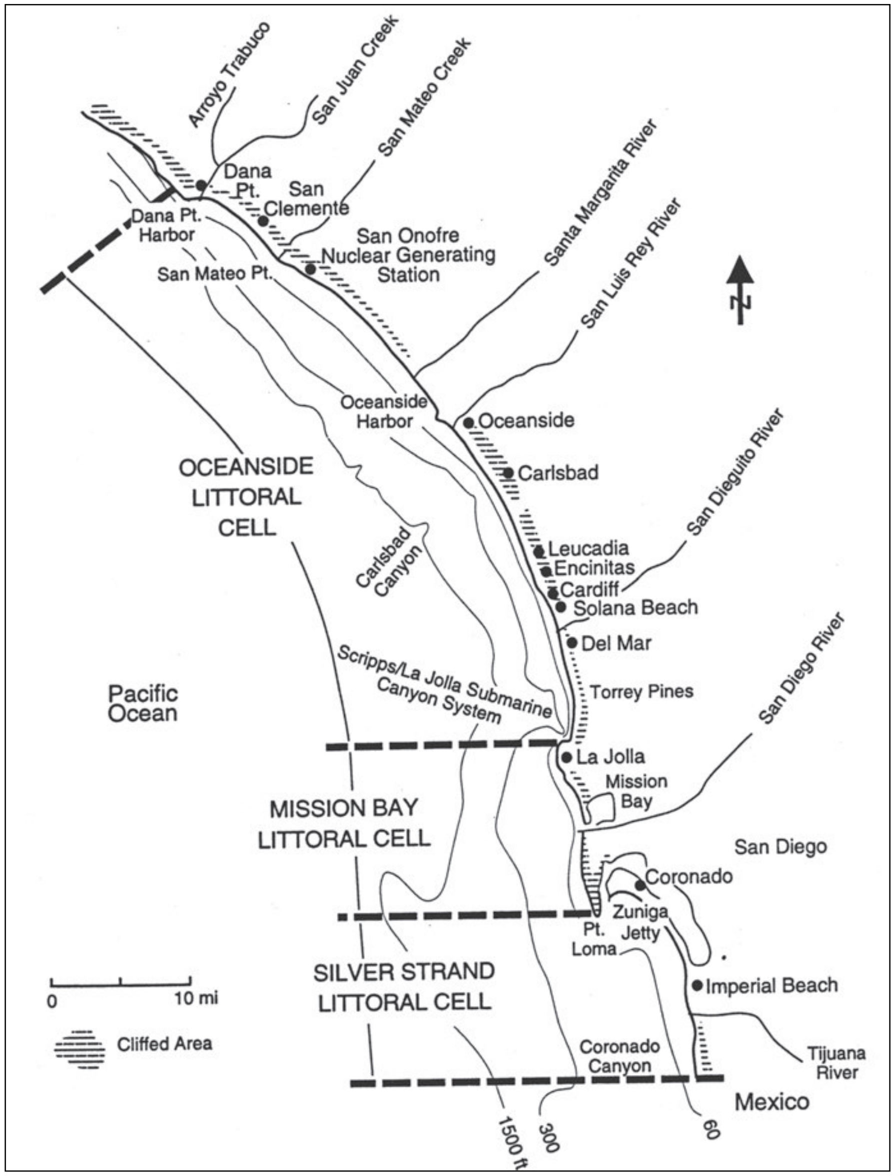


Figure 1. Map showing San Diego region littoral cells, including the Oceanside cell where the San Onofre Nuclear Generating Station is located (from Flick 1994).

There is strong evidence from the present measurements that the laydown pad sand and the upcoast filet beach split into two sand bulges that remained within a few kilometers (one north and one south) of SONGS for several years. Osborne and Yeh (1991) and Grove, *et al.* (1987) also noted this fact. Directional wave measurements (Schroeter *et al.* 1989) made during 1985-1986 support the suggestion that there has been no persistent tendency to transport the laydown pad material downcoast systematically or rapidly, contrary to expectation (Inman 1987).

BEACH MONITORING ACTIVITIES

Monitoring activity useful for studying beach changes at SONGS consisted of beach profiling, sand sampling, and aerial

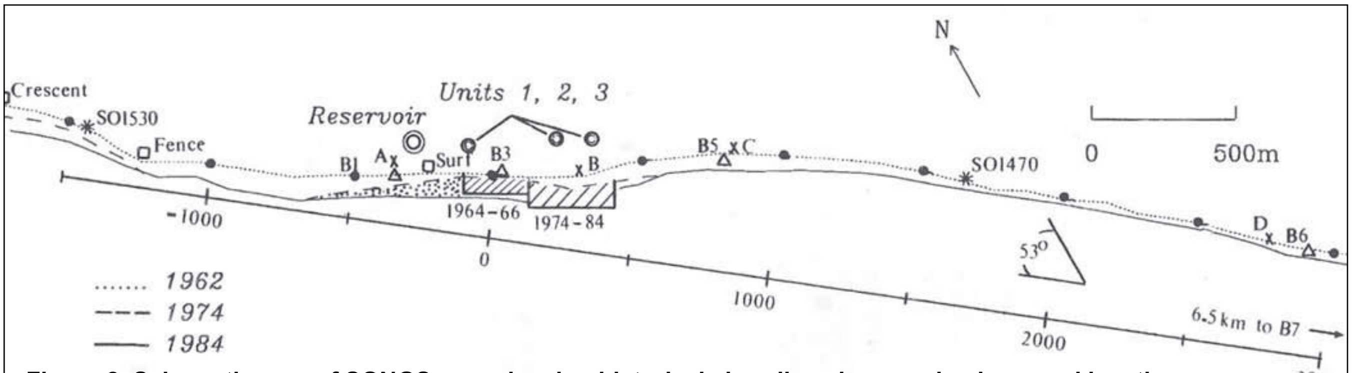


Figure 2. Schematic map of SONGS area showing historical shoreline changes, laydown pad locations (1964-1966 and 1974-1984) and later fillet beach (stippled). Scaled axis shows longshore coordinate distances during 1985-1989 surveys described in the text.

and ground photography. The most useful information for quantifying beach changes consists of the profile measurements. Sand samples have recently found use in confirming profile data results regarding dispersion of the laydown pad material after release (Osborne and Yeh 1991). The photographs taken at SONGS were generally required to satisfy water quality permit conditions. Thus the beach usually appears at the edge of the aerial photos, making distortion a problem for quantitative measurements. Nevertheless, important qualitative information can be gathered from the many sets of both ground and aerial photos taken between 1962 and 1990.

Figure 2 shows a schematic map of the SONGS area. The locations of benchmarks used over the years for beach profiling are indicated by letter designations. SCE sponsored profile measurement efforts that coincided with construction work, and generally ceased in between building activities.

Early data were collected in the area by Shepard (1950a, 1950b) at four range lines, three of which are shown in Figure 2 as squares and labeled "Crescent," "Fence," and "Surf." The method of horizon leveling was used and only selected profiles were plotted and published (Shepard 1950b). Shepard's original survey notes are available in the Scripps Institution of Oceanography Archives. Efforts to reconstruct the Shepard profiles were unsuccessful.

Berm width statistics of the three beaches were published (Shepard 1950b). "Fence" beach width data were taken each year from 1945 to 1949 in sufficient detail to define a "reversed" seasonal configuration. The beach was roughly 25 m wider in winter than in summer, which Shepard (1950b) attributes to the existence of a rock outcrop south of the cove. The outcrop acts to block the winter-time southward transport and thus widen the pocket at that time. "Crescent" and "Surf" beach were monitored much less frequently and show virtually no seasonal changes.

Benchmarks A, B, C, and D (x's, Figure 2) were established in 1964 and profiles were taken quarterly until early 1968

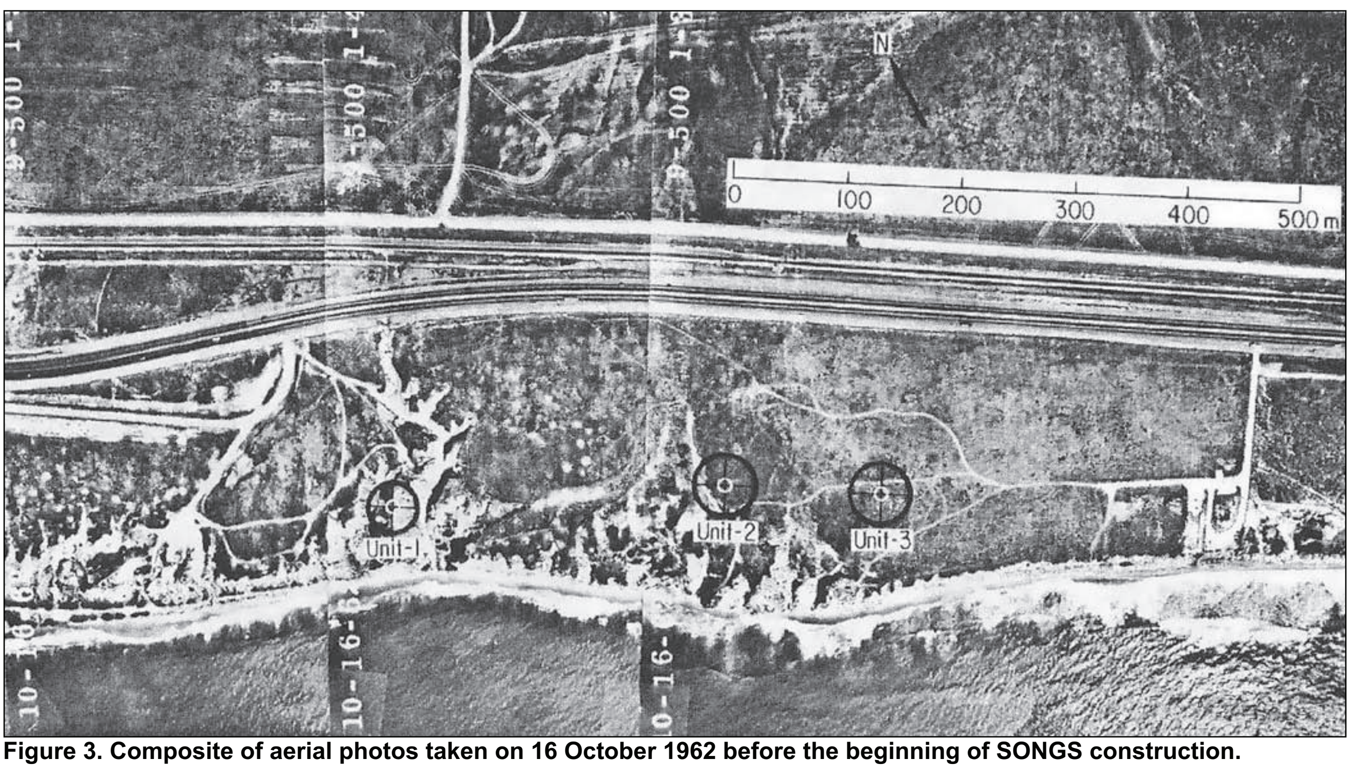


Figure 3. Composite of aerial photos taken on 16 October 1962 before the beginning of SONGS construction. Eventual locations of Units 1, 2, and 3 are shown. Note the narrow beach width throughout the area, and the natural point of land at the Units 2 and 3 site.

by Marine Advisers, as consultants to the power company. This period corresponds to the time Unit 1 was being built. Note that Figure 2 also shows the location of the Unit 1 laydown pad (hatched), which was in existence from 1964-1966.

Benchmarks B1, B3, B5, B6, and the remote B7 (triangles, Figure 2) were established in 1974 at the beginning of Units 2 and 3 construction. These were monitored monthly from 1974 through early 1980 and again in 1985, by SCE. The Units 2 and 3 laydown pad that was in existence from 1974 through 1984 is also shown in Figure 2. The survey period corresponds to the time of Units 2 and 3 construction and the period just before sand pad release.

Table 1 gives a list of the historical benchmarks and their Lambert and MRC coordinates for easy cross-reference. The final set of profile measurements (dots, Figure 2) were begun in May 1985 and concluded in September 1987, with nine sets of profiles taken. A follow-up survey was carried out in January 1989 and beach widths from these profiles are included in this discussion. Wading depth profiles were measured every 500 m along the beach, generally from -2,000 m (north) to +3,500 m (south). The longshore distance designation corresponds to the MRC coordinate system shown in Figure 2.

BEACH CHANGES DURING SONGS CONSTRUCTION

Sand supply

The "Provisional Construction Permit" authorizing SONGS Unit 1 was issued by the United States Atomic Energy Commission on 2 March 1964 (SCE 1964 Item 7). Construction activity began soon after, and by mid-1964, massive cliff excavations and other beach works were underway. Figure 3 is a mosaic of aerial photographs taken in 1962, before construction activity began. Note the narrow beaches typical of this area. The present location of Unit 1 and Units 2 and 3 have been superimposed as shown. Figure 4 is a photograph taken in June 1964 at a location about 1,160 m south of the construction site.

Figure 4 shows two crane booms in the background lifting sheet piling into place for the Unit 1 laydown pad. Note the extensive cobble patch and relatively narrow beach configurations, shown in Figure 4, typical of the San Onofre region before construction activities began (Shepard 1950a, 1950b). Figure 4 also shows evidence of cliff undermining by wave action at the base. By July 1964 (Figure 5) a thin veneer of sand had covered the cobbles at this location. The beach was still relatively narrow, as evidenced by kelp and debris at the cliff base. The sand accumulation at this location between the June and July 1964 photographs was probably due to normal, seasonal beach accretion, as opposed to construction activity. Early photographs of Unit 1 construction are shown in Figures 6-10.

Note from the map in Figure 2 that Station "A" is located just upcoast of Unit 1 and Station "B" is located just south of Unit 1. Figure 6 shows the north wall of the laydown pad being built using interlocked sheet pile driven into the sand. Figure 7, looking north shows

Figure 4. Photo taken 28 June 1964 near the southern end of the SONGS property looking north showing narrow beach with cobbles.

Figure 5. Photo taken 13 July 1964 at same location as Figure 4 looking south and showing sand cover over cobbles, but a still relatively narrow beach with water reaching cliff base at high tide.

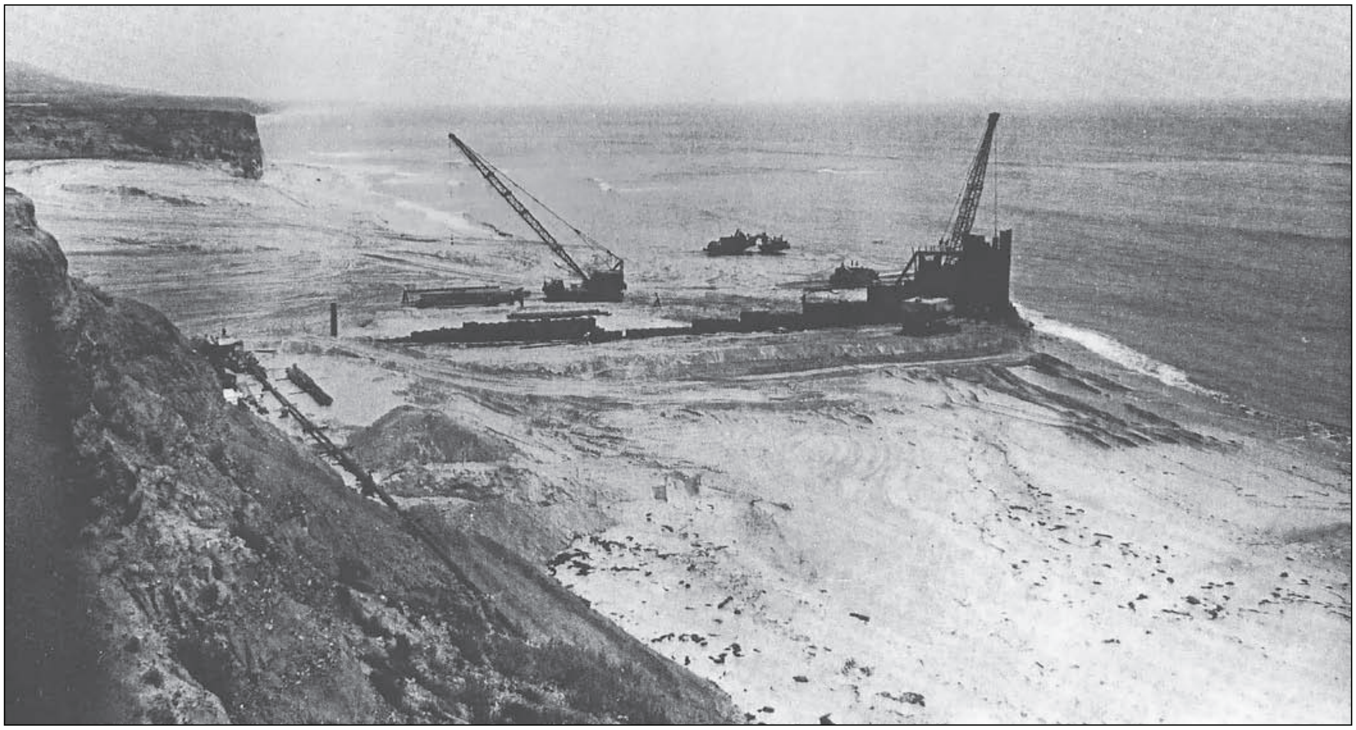


Figure 6. Photo showing construction of north wall of Unit 1 laydown pad on 4 June 1964 from Station A (see Figure 2).

Table 1. San Onofre historical beach profile benchmark designations.

BENCHMARKS	SURVEY DATES	LAMBERT COORDINATES* North	East	MRC COORDINATES** X (longshore)	Y (on-offshore)
CRESCENT	1947-49			~-1750.	~800.
FENCE	1945-49			~-1250.	~740.
SURF	1946			~-250.	~790.
A	1964-68	440,745	1,599,845	~422.	750.
B		439,605	1,601,645	225.	803.
C		438,890	1,603,260	750.	925.
D		434,620	1,608,215	2,739.	794.
B-1	1974-80, 1985	440,664	1,599,927	-387.	745.
B-3		440,038	1,601,034	-3.	796.
B-5		438,800	1,603,222	757.	896.
B-6		434,350	1,608,436	2,842.	769.
B-7		418,779	1,623,311	9,320.	-292.
SO-1530	1983-88	442,900	1,597,300	-1,437.	808.
SO-1470	1983-87	437,000	1,605,300	1,593.	839.

*California State Coordinate System — Lambert Grid Zone VI (meters)
** MRC coordinates — origin at Unit 1 outfall, X-coordinate positive downcoast, Y-coordinate positive onshore and 37° east of true north (meters).

the massive cliff cuts made at the site. Eventually, about 1 million m^3 of material was excavated from these cliffs. Note the contact line in the cliff between the lower San Mateo sand formation and the overlying darker, finer, terrace deposits (Figures 4, 6, and 7). About 60% of the excavated material consisted of terrace deposits and 40% of San Mateo sands.

The terrace deposits were unsuitable for disposal on the beach or in nearshore waters because of the turbidity they would cause (SCE 1964 Items 6, 8, 9, 10, 11, and 14). These were used to fill "barancas" (small canyons) or spread evenly on the mesa tops and compacted. The San Mateo sand was partly used to fill the newly constructed laydown pad (120,000 m^3) with the remainder (280,000 m^3) bulldozed onto the adjacent beach face for beach nourishment, as illustrated in Figures 6-8 (SCE 1964 Item 9). It was recognized that the San Mateo formation contained a small percentage of very fine material, including inclusions of clay. Estimates of the fine fraction (silt and clay, smaller than 1/16 mm) range from 6% (SCE 1964 item 10) to about 15%. Figure 9 shows the start of construction of the trestle used to place the Unit 1 cooling water pipes.

Figure 10 shows the cumulative amount of sand that was made available to the nearshore during SONGS construction activities, as a function of time between 1964 and 1985. The approximately 1 million m^3 of sand that was released over the 21-year period amounted to an average annual sand influx of almost 50,000 m^3 per year. This amount is of the same order of magnitude as the average sediment delivery of San Juan Creek, located about 16 km north of SONGS, near Dana Point, and the only nearby river with long-term yield data.

San Mateo and San Onofre Creeks (nearby to SONGS) together yield between two and four times less sand than San Juan Creek (Simon, Li and Assoc. 1988, State of California 1977). Figure 11 shows the sediment yield from San Juan Creek plotted from data tabulated in Simon, Li and Assoc. (1988). The river output from 1920 to 1983 is about 2 million m^3, assuming a conversion factor of 2 tons/m^3. This amounts to approximately 31,000 m^3 per year. The sand yield during the period 1965 to 1985, coinciding with construction activities at SONGS was likely much larger than normal due to the occurrence of several extremely wet winters (1969, 1978, 1980, and 1983) in this period. For this 20-year span, approximately 1.5 million m^3 of sediment were delivered, or about 75,000 m^3 per year on average.

Figures 12 and 13 are aerial photographs of the reach from San Mateo Point to SONGS, showing the locations of San Mateo and San Onofre Creeks. Figure 12 was taken in September 1974, during a period of relatively low rainfall. Note that the creek beds are dry (as is typical in normal, dry summers) and that the creek mouths have been closed by the littoral sand drift. San Mateo Creek actually has a concave shaped beach at the mouth, which is visible below the cloud cover. Contrast this (accounting for a change in scale) with Figure 13, taken in late March 1980 when both creeks have substantial sand deltas at the shoreline. There is also evidence of pronounced southbound littoral drift from the configuration of the sand spits near each creek mouth. Note that the beach discharge point of San Mateo Creek is almost 1 km south of the river mouth.

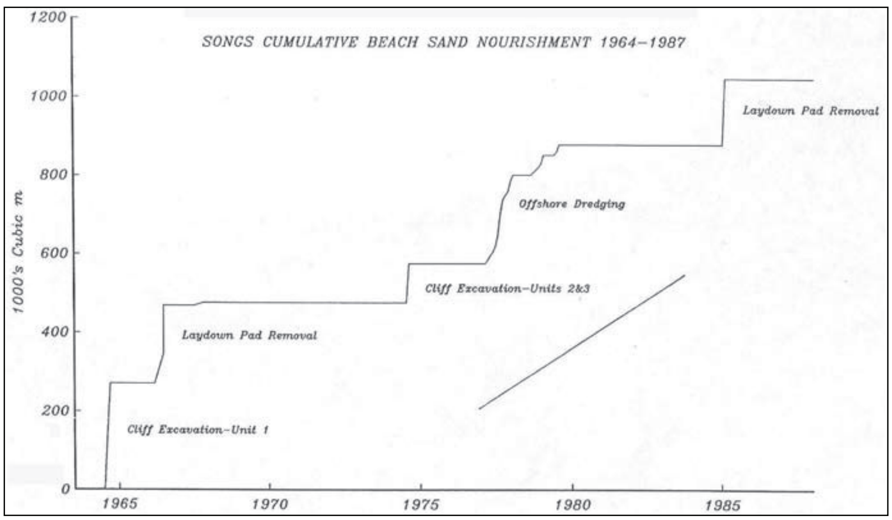
Sediment yield estimates from San Mateo and San Onofre creeks over the 20-year construction period range from a low of about 19,000 m^3 per year to a high of about 38,000 m^3 per year (Simon, Li and Assoc. 1988, State of California 1977). The discharge from these sources would also be highly episodic, occurring mainly in 1969, 1978, 1980, and 1983. It is apparent that construction-related sand contributions exceeded the natural sand supplies from the adjacent rivers over this time span. This is significant in view of the fact that several very wet years occurred during this time, and that stream yield may have been more than twice its long-term mean. In other words, the 50,000 m^3 per year artificial nourishment during SONGS construction may have exceeded the long-term, local river input of sand by as much as a factor of five.

Figure 7. Photo similar to Figure 6, but looking north from Station B.

Figure 8. Photo taken 24 June 1964 from Station A showing sand spoil from continued cliff excavation and most of the Unit 1 sheet-pile laydown pad completed.

Figure 9. Photo taken 30 January 1965 looking south toward Unit 1 laydown pad and the beginning of construction of the trestle used to lay the cooling pipes.

Figure 10. Cumulative sand volume deposited on San Onofre Beach from SONGS construction-related activity from 1964-1985. Sloping line indicates average value of 50,000 m³ per year.



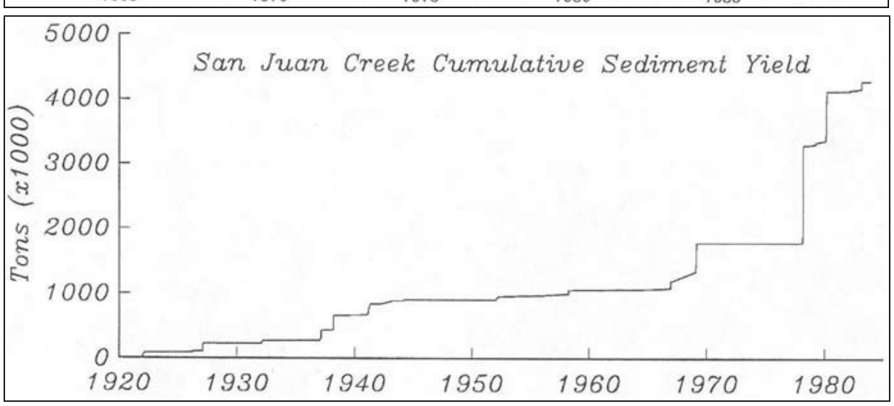


Figure 11. Cumulative sediment yield 1920-1985 from San Juan Creek located about 16 km north of SONGS.

BEACH CHANGES 1964-1968

During 1965, the beach at stations "A" and "B" widened rapidly as a result of the cliff excavation. This is documented by the beach width data shown in Figure 14. Beach width was taken as the distance from the benchmark to the point where the profile crossed the NGVD ("Mean Sea Level") elevation datum. All profile data presented in this paper have been reduced to beach width, to facilitate comparison.

Typical seasonal beach width changes reported by Shepard (1950a, 1950b) at San Onofre were about 15 m at "Surf" and 20 m at "Crescent" (Figure 2). These values are slightly lower than changes observed at beaches farther south in the littoral cell. At Del Mar, for example, Flick and Waldorf (1984) found 30 m seasonal variation, averaged over about 10 years from 1974-1984. Yates *et al.* (2009a) found similar, smaller values of beach width change at San Onofre in 2005-2006, but up to about 40 m changes at Torrey Pines from 2003-2008 (Yates *et al.* 2009b). Subaerial sand volume changes corresponding to these beach width values at San Onofre amount to about 50 m^3/m, again for "typical" conditions. Of course, heavy wave attack combined with elevated sea levels can cause beach narrowing of 60-90 m and corresponding sand volume cuts of 100-150 m^3/m (Flick *et al.* 1986).

The 1 million m^3 of sand supplied to the San Onofre beaches during the 21-year construction activity amounted to about 50 $m^3/m/yr$, if we can assume it was all deposited 0.5 km up or downcoast of SONGS. This amount is equal to typical seasonal beach volume changes and is one important reason why the local beaches widened. The width at both stations "A" and "B" increased about 50 m (Figure 14) between the pre-construction survey of May 1964 and July 1964 (Marine Advisers 1969).

After the cliff excavation was concluded, the beach at station "B" retreated through early 1965. At that time, offshore dredging activity occurred as the cooling water pipes for Unit 1 were laid. Figure 9 shows the trestle that was used for this purpose. The offshore excavation resulted in additional sand supply to the beach, although the exact quantity and timing is not well documented[1]. The beach at station "C" retreated slowly in width (Figure 14) throughout the survey period, although the subaerial volume (not shown) increased slightly (Marine Advisers 1969). This suggests that the subaerial beach steepened during this period or that the berm became significantly

1) As an approximation, we could use the volume occupied by the Unit 1 intake and diffuser pipes, which are each about 4 m in diameter and 1,000 m long, amounting to approximately 25,000 m^3. This amounts to only 2.5% of the total construction sand contribution.

higher. Not much activity was observed at range "D" which is located about 2,700 m south of Unit 1 (Figure 2). Some beach width changes occurred at "D" starting in early 1966, about 18 months after the start of construction. Whether this can be related directly to the increased sand supply using the present data is doubtful, in view of the wide spacing of profiles in space and time.

Later work, described below, suggests that beach changes due to construction related nourishment can be confined to the vicinity of SONGS for years. Unfortunately, following completion of Unit 1 construction in 1968, beach monitoring activity essentially ceased.

BEACH CHANGES 1974-1984

Surveys and aerial photography started again in 1974 to monitor changes related to construction of SONGS Units 2 and 3. As described above, beach monitoring during construction of Units 2 and 3 was expanded. Profile measurements were done monthly on five ranges denoted B1, B3, B5, B6, and B7 (Figure 2). The total impact of Units 2 and 3 construction on the beach configuration was much larger than that from Unit 1. This was partly related to the slightly larger excavated sand volume (Figure 10), but was mainly due to the longevity of the laydown pad. The Units 2 and 3 laydown pad was installed in early 1974 and removed starting in December 1984. It was filled with about 168,000 m^3 of San Mateo sand.

Figure 15, taken on 3 July 1974 shows cliff excavation and most of the sheetpile laydown pad in place. Note the substantial fillet beach formed at the north side of the pad and the beach widening taking place in front of Unit 1. The area downcoast of the new pad also shows a fillet beach, no doubt because of the cliff excavation sand supply. Figure 16 shows a history of beach width measurements starting in 1974 to 1980 and 1985. Referring again to the map in Figure 2, note that Ranges B1 and B3 are upcoast of the laydown pad. Ranges B5 and B6 are downcoast of the pad, while Range B7 is downcoast and remote, being about 10 km south of the pad.

Beach widths increase sharply at Ranges B1, B3, and B5 during initial work in 1974. Range B5 peaks in early 1975, when the major cliff excavation is finished. Beach widths at the upcoast Ranges B1 and B3 continue to increase to

Figure 12. Aerial photo composite of the area between San Mateo Creek and SONGS taken 9 August 1974 about five months after Units 2 and 3 construction began. This was a period of drought with low rainfall and river flow — note the indented shoreline at the mouth of San Mateo Creek (upper part of figure, under cloud cover).

Figure 13. Aerial photo taken 26 March 1980 after substantial flooding occurred in southern California. Note sand deltas at San Mateo and San Onofre creeks (upper and middle). There is now a delta formation at San Mateo Creek and shoreline is convex, in sharp contrast to Figure 12. Note sand bypassing at the Units 2 and 3 laydown pad (lower).

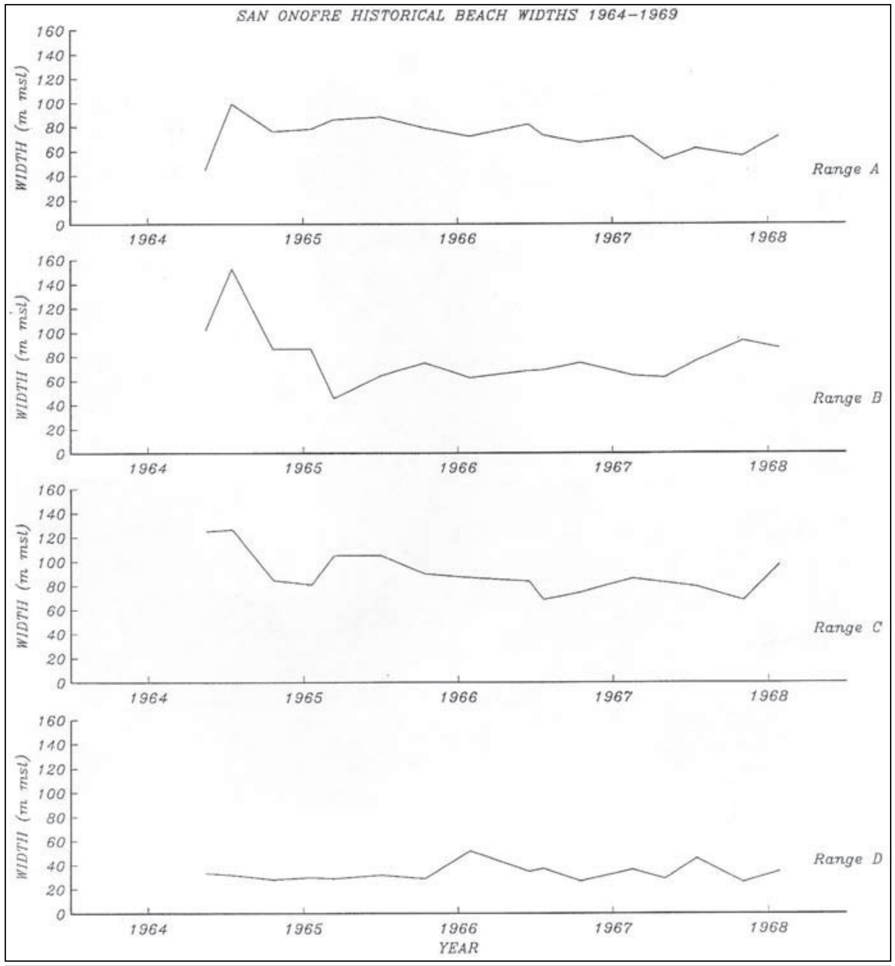
about 1979, when they seem to stabilize just before data-taking stopped. Overall, beach widths increased by about 80 m at B1, and about 100 m at B3 between 1974 and 1980. Range B5 shows a decline in width starting in 1975, but remains wider than pre-construction values. Several seasonal fluctuations in B5 may be seen with peaks in beach width in the winters of 1977-1980. These are out of phase with seasonal changes visible at Range B3, and correspond to "reversed" conditions for southern California.

Figure 17 shows a photograph dated 25 April 1977 taken during construction of the trestles used to lay the cooling water pipes for Units 2 and 3. Note that the fillet beach north (bottom of photo) of the laydown pad is actually wider than the pad. This suggests that wave action was effective at bypassing sand around the pad, thus limiting the growth of the upcoast beach. This also had the effect of stabilizing the expected erosion downcoast of the pad. Again, this is consistent with measurements made at B5, where mean beach width does not change from 1977 onward.

At this time the laydown pad structure could be thought of as an extension of the natural "point" land feature present at this location (Figure 3). Once sand bypassing commenced, there was very little net effect on the shoreline due to the structure. Data from Ranges B6 and B7 show little net or seasonal change over the measurement period. Both these ranges (especially B7) seem to be too far downcoast to be affected by either the sand nourishment or the laydown pad. By early 1980, when the photograph in Figure 18 was taken, river flooding had increased local sand supplies yet again, as described above. This had the effect of widening the beaches to an additional, unknown degree in the entire area. This can be seen qualitatively in Figure 18, which clearly shows substantial sand volumes in front of the laydown pad. Unfortunately, quantitative data is lacking for this period. Data-taking resumed in late 1984, at the start of laydown pad removal. Figure 16 suggests, but does not prove that there were no large, net changes in beach width during this interval, although short term increases probably occurred after the floods of 1980 and 1983.

The laydown pad was completely removed by early 1985. This served to contribute another, and final, 168,000 m^3 of sand to the beach (Figure 10). From this time forward, the history of beach widths is essentially one of retreat. However, there are a number of important features to this retreat that were unanticipated.

Figure 14 (right). Beach width time histories from surveys conducted around the time of Unit 1 construction from 1964-1968. Note sharp increase in beach widths at Ranges A and B due to cliff excavation and a gradual return to equilibrium. The remote Range D showed no net change (data from Marine Advisers 1969).



BEACH CHANGES 1985-1989

Comparison of the beach widths in the area between Unit 1 and Units 2 and 3 shown in Figure 18 with those in Figure 19 (allowing for the 2X scale factor) illustrate the dramatic narrowing about three years after laydown pad removal by early 1985. Note that the beach adjacent to Units 2 and 3 had retreated almost to the seawall by the time the photograph in Figure 19 was taken on 25 January 1988. A more detailed view of the beach narrowing adjacent to Units 2 and 3 can be seen in Figure 20. This is a composite of four aerial photographs of the laydown pad taken between 4 December 1984, just before removal began (left) and progressing through partial removal (11 January 1985), complete removal (5 February 1985), and about one year later (12 December 1985), when the dry beach had partially disappeared at the center of the point (right).

Quantitative beach width change measurements taken as part of the last phase of monitoring are shown in Figure 21. The area of the laydown pad is stippled in the upper panel, which also shows the shoreline position at the start of measurements in May 1985. The shoreline position is plotted relative to the MRC longshore coordinate system (shown with tics from -2,000 m to +3000 m, north to south, Figure 2) and relative to an arbitrary on-offshore coordinate system, centered at the mean shoreline position for convenience.

Referring to Figure 21, the lower 9 traces show shoreline changes relative to the original May 1985 shoreline. Each trace is offset by 50 m (dashed axis) for clarity. Beach profile measurements were made from fixed benchmarks spaced every 500 m alongshore from -2,000 m to +2,000 m. Later, the area was expanded to +3,500 m, in anticipation of downcoast transport of the laydown pad material.

Beach width was measured off each profile line as the distance from the benchmark to the intersection of the pro-

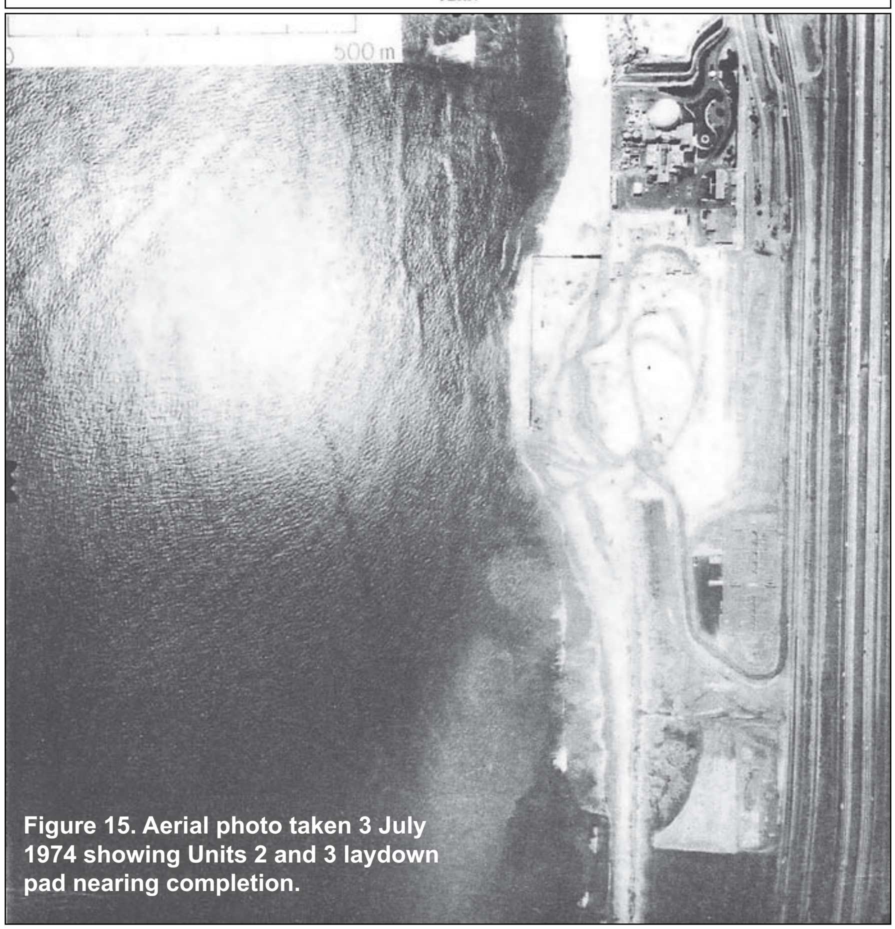


Figure 15. Aerial photo taken 3 July 1974 showing Units 2 and 3 laydown pad nearing completion.

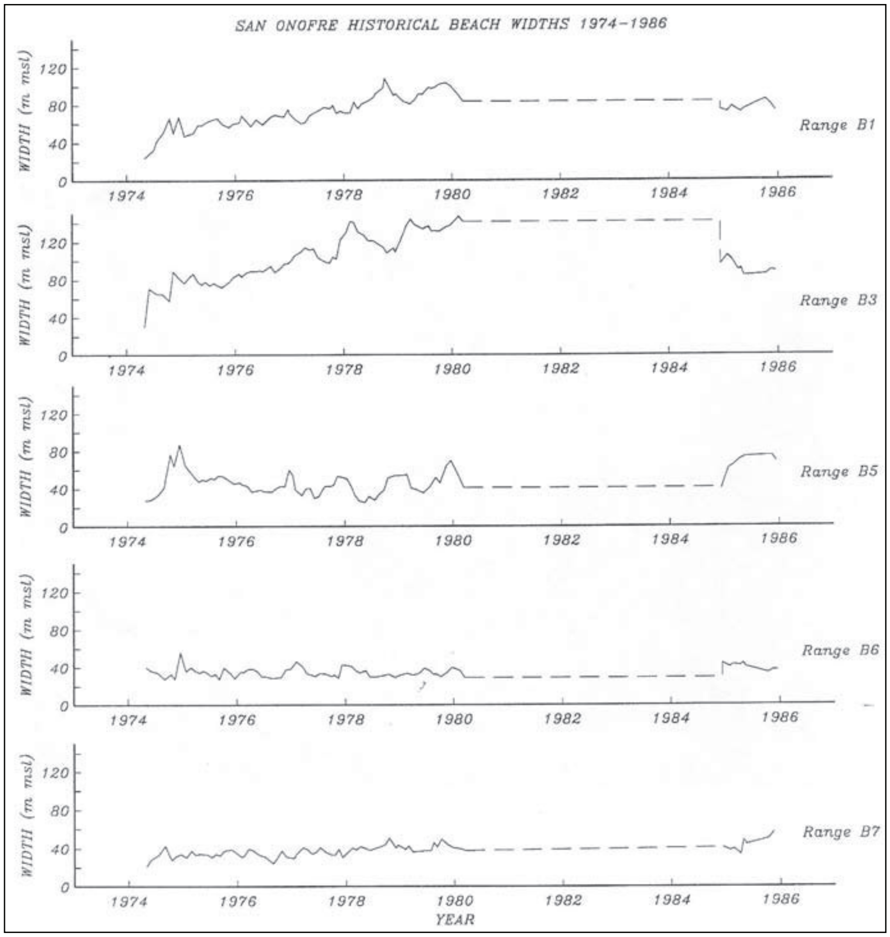


Figure 16. Beach width time histories from 1974-1986 surveys conducted over and beyond the time span of Units 2 and 3 construction. Note the widening of the beach at Ranges B1 and B3 due to cliff excavation and interruption of longshore transport by the laydown pad.

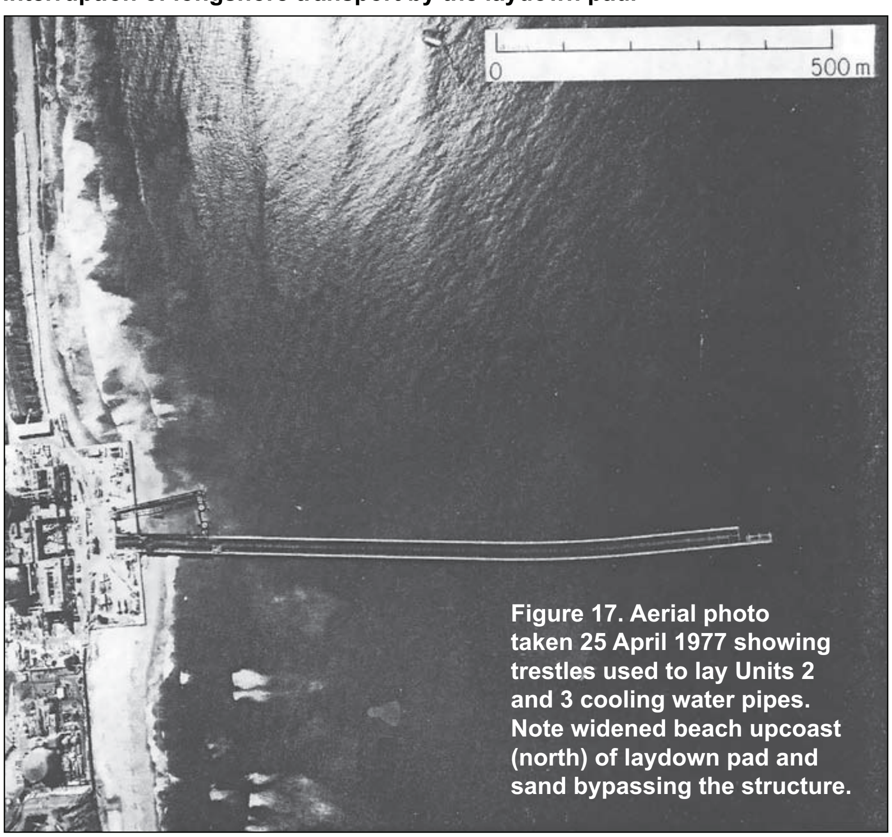


Figure 17. Aerial photo taken 25 April 1977 showing trestles used to lay Units 2 and 3 cooling water pipes. Note widened beach upcoast (north) of laydown pad and sand bypassing the structure.

file with the mean-sea-level datum. The changes in beach width for each profile date (shown on the right) relative to May 1985 are plotted in Figure 21. Positive values indicate widening, negative values denote erosion. Interestingly, there was relatively little change in beach width from May 1985 through October 1985, except for a small accretion at range -1,000 m. This is consistent with the idea that material from either the laydown pad or the adjacent fillet beach moved northward, upcoast, under the summer wave regime.

Wave measurements in Schroeter *et al.* (1989) suggest that the mean longshore transport potential was indeed to the north from about April to October 1985. Noticeable changes in beach width occurred between October 1985 and the next set of profile measurements in March 1986. There was narrowing everywhere from -1,000 m to +500 m, and the development of two bulges, one at -1500 m and the other at +1,000 m. The narrowing represents a cut of about 10 m, and the downcoast bulge at +1,000 m is an accretion of about 20 m. This shoreline configuration is the first evidence of a bifurcation of the laydown pad sand material into two bulges. The bulges are persistent for at least two years and perhaps three, as evidence for them can be seen in the profile change data taken in September 1987 and January 1989 (bottom of Figure 21).

Beginning with the March 1986 data, there is a continuous narrowing of the beach adjacent to the power plant, around Range 0. The last profile data (January 1989) show nearly a 50 m decrease in beach width compared to May 1985. The downcoast bulge, which apparently moves farther south than +1,500 m, grew to about 25 m width by September 1987 and eroded slightly by January 1989. The upcoast bulge near -1,500 m continued to decrease in width from March 1985 to at least May 1987 when data taking stopped on that range. The downcoast bulge is clearly visible on the photograph shown in Figure 19, where there are a series of rhythmic features about 1,500 m south of Unit 1.

Overall, there is a net shoreline width decrease, averaged over all sampled ranges over the sample period. This is reflected in the statistic shown under the survey date next to each line in Figure

Figure 18 (top). Aerial photo taken 7 February 1980 showing area from San Mateo Creek to SONGS. Note extensive beach widening over entire reach due to sand from the river and construction activity. Sand bypassing of the structure limited downcoast (southward) beach loss.

Figure 19 (bottom). Aerial photo taken 25 January 1988 showing greatly reduced beach width adjacent to SONGS Units 2 and 3 seawall, in contrast to Figure 18. Note persisting beach width bulges north and south of SONGS.

21. For example, there was a retreat of 5.91 m over all ranges on the October 1986 survey, again compared with the May 1985 baseline. By January 1989, the net erosion was 14.13 m, as shown. The net decrease in beach width, and presumably sand volume, is consistent with at least some offshore transport. The relative volumes of offshore transport and longshore transport out of the area cannot be evaluated with the present data, since the profiles only extend to wading depth, generally -1 m or so. The fact that no rapid or even consistent downcoast transport of the sand bulges occurred suggests however, that substantial sand volumes did move offshore.

It is interesting that the laydown pad material separated into two bulges. The fact that it did has been confirmed by grain shape analysis studies published by Osborne and Yeh (1991). This work showed that sand grains from the laydown pad were transported both north and south a distance of about 1.5 km. Samples from these locations were found to be enriched in grains of lower angularity (smoother or rounder) than the San Mateo sands that were used to fill the laydown pad. This smoothing of San Mateo grains was presumably caused by the heavy equipment traffic on the laydown pad crushing and grinding the sand grains. Osborne and Yeh (1991) report smoothed grains at two horizons, one corresponding in time to the Unit 1 laydown pad (1964-66), and the other to the Units 2 and 3 pad (1974-84).

Figure 21 suggests that after formation of the two sand bulges, these features moved alternately up and downcoast with time, depending presumably on the prevailing longshore wave transport potential. Measurements of wave direc-

Figure 20. Composite of four aerial photographs of Units 2 and 3 laydown pad taken between 4 December 1984, just before removal began (left), and 12 December 1985 (right) after beach had narrowed.

tion statistics from late 1984 to late 1986 have been presented by Schroeter *et al.* (1989), as mentioned previously. These data are qualitatively consistent with the observed motions of the bulges over the same period as shown in Figure 21. Another striking feature of the wave data, at least over the indicated time interval, is that there is a close balance between southward directed and northward directed momentum flux. This is consistent with the observation (Figure 21) that the laydown pad material remained in the vicinity of SONGS, or at most, moved offshore, as discussed above. It is contrary to the expected, relatively rapid downcoast dispersal anticipated at the beginning of this study (Wanetick and Flick 1986, Flick and Wanetick 1989) and predicted by Inman (1987).

CONCLUSIONS

The anthropogenic sand contributions and sand retention structures associated with the prolonged, 20-year construction activity at SONGS from 1964-66 and 1974-84 provides a rare opportunity to document a complete cycle of beach change in southern California from relatively narrow, to wide, and back to narrow following removal of the structures. The main conclusions of the monitoring effort that tracked these changes are:

• Sand placement and sand retention structures in southern California can undoubtedly widen beaches and maintain their width beyond their natural state;

• Once the beach is wide enough for wave action to bypass sand around a structure, the down-coast beach width is essentially unaffected by the structure;

• Sand placed at San Onofre remained in the vicinity or moved offshore, but did not migrate in a noticeable bulge rapidly down-coast (southward) as expected.

EPILOG

SONGS Unit 1 was retired in 1992. Its reactor was subsequently removed and the containment building used for a time to store spent fuel. By 2008, the 40-year-old Unit 1 had been completely "deconstructed" and removed. Units 2 and 3 are expected to be in operation until 2050, providing about 20% of southern California's electricity needs. A double-seawall arrangement allows lateral beach access and transit along the beach in front of Units 2 and 3. The beach remains narrow at and around SONGS.

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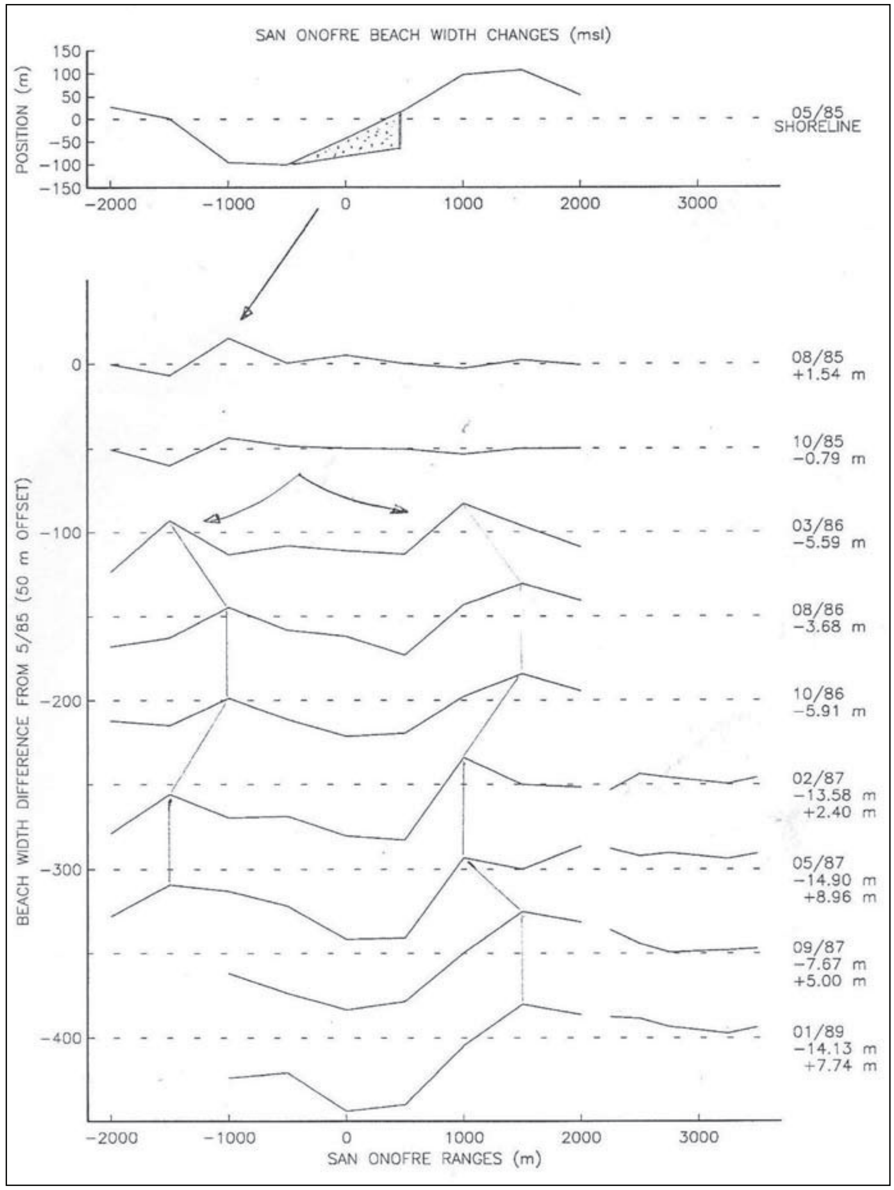

Figure 21. Time history of beach width changes in the vicinity of SONGS in 1985-1989, following removal of the Units 2 and 3 laydown pad. Lower curves show changes in beach width relative to May 1985 survey at the dates indicated on the right. Surveys are offset 50 m for clarity.

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