Wave Action and Damage at the Galveston Sea Wall Resulting from Defective Toe Protection

by

Frank D. Masch
and
Walter L. Moore

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I. Introduction.

During Hurricane Carla, September 9 through 12, 1961, the southwest end of the Galveston sea wall was heavily attacked by wave action. As a result, extensive areas of the concrete toe protection part of the wall were severely damaged, the roadway paralleling the wall was undermined, and the backfill behind the wall was subject to extensive erosion. This report has as its basic purpose to investigate the factual issues now before the Board for determination. These issues are (as stated in Stipulation).

1.) Was there a deficiency in the design of the seawall in so far as the toe protection part thereof was concerned.

2.) Did the lowering of the toe protection cause a significant increase in overtopping and water going over the top of the seawall during the storm, and if so, was there substantial erosion, structural damage and any other damage caused thereby.

In this report it is intended to show that there was a deficiency in the design of the toe which led to its failure. This in turn subsequently caused an increase in overtopping and water going over the wall resulting in severe scour and erosion.

A list of exhibits to which reference will be made is included at the end of this report. In so far as possible, these items carry the same categorical designation used in the Stipulation.

The project under consideration here is that covered by Contracts Nos. DA-41-243-CIVENG-60-70 and -60-77 and runs from Sta 94/00 to Sta 163/85 a distance of 6985 feet. The seawall is a curved gravity-type pile-supported concrete wall with an embankment in the rear. Sidewalks and roadway parallel to the wall are on the embankment. A typical section of the wall illustrating significant features can be seen in Exhibit 2a. Of particular interest is the toe protection for this section of the wall. The toe protection was made up of interlocking precast concrete blocks 6 feet long, 3 feet deep and varying from 3 feet 5 inches to 4 feet 5 inches in width for interlocking action. These blocks were set 1 inch apart. The seaward side of the toe protection blocks was originally set with the top surface at elevation 3.1 feet, and at the sea wall, the corresponding elevation was 4.1 feet. These blocks were set on a gravel filter blanket and a small row of rip-rap was to be placed at the most seaward edge of the toe blocks. Reference Exhibit 2a.

II. Description of Storm.

Much of the meteorological data on Hurricane Carla has been conveniently summarized in the Corps of Engineers, Hurricane Carla Report of January, 1962, (Exhibit 2h). Generally speaking the storm was considered to have lasted from September 9 - 12, 1961. Hurricane Carla originated about 250 miles east southeast of Cape Gracis, Nicaragua. The storm center moved generally northwest across the Caribbean, through the Yucatan Channel and then across the Gulf of Mexico. The eye of the storm crossed the coastline in a northerly direction near Port O'Conner on Monday, September 11, at about 3:00 P.M., and then moved almost due north for some distance inland. The nearest approach of storm center to Galveston was about 120 miles West of Galveston. The tide at Pleasure pier in Galveston remained near its maximum of 9.3 feet from 1:00 A. M. to 3:00 P.M. September 11.

During the period of the hurricane, 15.32 inches of rainfall was recorded at Galveston. It is interesting to note of this total 11.27 inches fell between 2:00 P.M. September 11 and 7:30 A.M. September 12, 1961, or about 75 per cent of the total rainfall fell after the eye moved inland and storm tides had begun to recede. (Reference Exhibit 2i).

While waves are certainly a very important part of hurricane phenomena, no measurements of wave characteristics are reported during Carla. Because of the very strong winds, the near shore area was a wave generating area, and in such areas it is quite common to find both wind waves and swell. The wind waves are shortcrested and steep with many of them breaking. The swell may be thought of as the longer period waves which move in from offshore. Thus it would be expected that a confused sea existed at the wall with a spectrum of wave heights and periods present. In the Carla report, the Corps of Engineers reports that "none of the waves exceeded about 0.8 of the depth of water in which they occurred. It is generally believed that waves higher than 0.8 of the depth would break". This statement is in agreement with theory for breaking waves (Reference 1) in which $H_b = (1/1.28)\, d_b = 0.78\, d_b$ where H_b and d_b are breaking wave height and depth respectively. On this basis it may be assumed that waves greater than 0.8 of the depth would have broken offshore.

With regards to the wave phenomena during Carla, it is important to note that at the time the storm tides were at a maximum, the winds were also at a maximum and came out of the east and southeast.

III. Damage to Project.

The stage of completion of the project is shown on Exhibit 2b which is a drawing entitled, "Drawing Shows Status of Work Completed Prior to Hurricane Carla". The drawing shows that the shoreward sidewalk was incomplete from Sta 121/30 to the west end of the project, and the rip-rap in front of the top protection was not in place. The toe protection blocks were not in place from Sta 162/30 to the end of the project at Sta 163/85. The asphalt wearing surface on the street paving was not in place, and the concrete blocks at the west end of the backfill were not in place. The backfill for the entire length of the project was in place, but with no top soil or grass cover.

The damage to the project after Hurricane Carla is summarized in Exhibit 2c1, 2c2, 2k, and 2d. The tie-beams under the north (shoreward) sidewalk were uncovered where the sidewalk had not been completed, the north highway lane was undercut and eroded from Sta 147/30 westward to the end of the project with the width of the eroded ditch increasing rapidly from Sta 158/15 to the west end of the project where the entire roadway was undercut. The pile cap on the north cutoff wall, some tie-beams and deadmen near the west end of the project were also damaged. (Exhibits 2c2 and 2d).

The toe protection blocks settled due to pumping of the sand from beneath them by as much as 6.5 feet. Extensive area of the toe protection dropped from 3 to 4.5 feet. A photograph of the lowered toe protection is shown as Exhibit 17 in Exhibit 2h. Exhibit 2k gives elevations of the toe protection blocks 5 feet from the toe of the wall and 25 feet from the toe of the wall. Initially the toe of the block elevations were at 4.1 feet at the toe of the wall and 3.1 feet at the outer edge of the blocks.

Detailed information on the damage due to erosion of the backfill and of the material under the unfinished sidewalks and the roadway is summarized on the set of cross sections, Exhibit 2c1, taken every 50 feet for the length of the project.

A study of these cross sections indicates a probable sequence of the erosion damage. It is seen, for example, that for the major portion of the length of the project the damage to the backfill was fairly uniform along the length of the project. At Sta 130/00 and westward, where the sidewalk was not in place, damage occurred in the sidewalk area. However erosion in the sidewalk area remained small up to Sta 144/00. At Sta 152/00 significant erosion of material under the sidewalk area is apparent and there is some erosion under the roadway. It is also apparent that from Sta 157/00 westward, the erosion of the sidewalk and roadway increases rapidly while erosion of the backfill decreases. This is especially apparent from Sta 161/00 westward.

The pattern of erosion damage strongly suggests the following as the probable cause and sequence of the damage. Wind and wave action during Hurricane Carla caused large quantities of water to overtop the sea wall, and be blown across the roadway, the sidewalk, and the backfill. The erosion of the backfill was due to this flow of water coming over the wall and being blown across the embankment. In the area where the sidewalk was not complete and the base material was exposed, there was some erosive attack on the base materials. Initially at the west end of the project where the water on the roadway could drain westward along the roadway to the sea, the erosion would be very rapid along the sidewalk course. This would produce rapid cutting both downward and sideways forming a gulley which would grow gradually upstream in an easterly direction. As this gulley enlarged it would intercept the water flowing across the top of the wall and carry it westward to the sea. This would gradually reduce and eventually eliminate the erosion of the backfill. Thus, in those areas near the west end of the wall, where the gulley or channel developed rapidly, erosion of backfill occurred for only a short time and the amount of material removed was small (Exhibit 2b, Sta 157/00 westward). For most of the length of the project erosion of the backfill continued for a longer duration producing extensive and fairly uniform erosion of the backfill.

IV. Causes for Overtopping.

As stated in Reference 1, page 87, "the primary purpose of a seawall or revetment is to protect the land and upland structures from damage by wave forces." Why was the damage to the backfill in this case more extensive than would have been anticipated? It is our belief that this damage was greater than anticipated because the amount of water coming over the wall due to runup and overtopping was greater than would normally have been expected. This increase in overtopping in turn was due to the dropping of the toe protection portion of the wall and the drop of the toe protection in turn was due to the inter-locking nature of the blocks and a deficiency of fine material in the filter blanket under the blocks.

The mechanism for the failure of the toe protection may be described as follows. Because of the absence of fine material in the filter blanket, fluctuating pressures from wave action created currents which penetrated the filter blanket and pumped fine beach sand up through the coarse filter and up through the space between the concrete blocks. As sand was pumped from beneath the blocks there was bridging action between adjacent blocks which allowed large scour holes to form under the blocks where water surged back and forth thus aggravating the pumping action. As the sand was pumped above the concrete toe protection it was carried offshore by the bottom return flow associated with the wind set-up. The bridging action also prevented the outer blocks from tilting as sand was scoured from in front. Consequently, extensive scour occurred, and the toe protection dropped from 1 to 6.5 feet with extensive areas dropping from 3 to 4.5 feet below the original elevation. In some areas, scour was of such an extent that it was possible to see back to the sheet piling underneath the sea wall.

It is interesting to note here that the blocks did not settle in the areas very near to the stairways leading down from the top of the wall. This is because the stairways served as deflectors and diverted the incoming waves and wind generated currents parallel to the wall. This, in turn, reduced the pumping action and the strength of the underflow so that sand was not washed away in these areas and the blocks were not undermined (Exhibit 2h).

To reduce the movement of the base material up through the toe protection by pumping action, the toe blocks are placed on a gravel filter blanket. If the voids of this filter material are much larger than the finest grains of the underlying natural base material, the fine sand particles will be pumped or washed up through interstices of the filter material and then up through the spacing between the toe protection blocks. To prevent this pumping action, the filter material must meet certain requirements with regards to grain size distribution. The Terzaghi-Vicksburg standards for a filter blanket (References 2, 3, and 4) show that a material will satisfy requirements if its 15 per cent finer than size, D_{15}, is at least 4 times, but less than 20 times as large as the D_{15} size of the base material, and less than 5 times the D_{85} size of the base material. In addition, the D_{50} of the filter material must be less than 25 times the D_{50} of the base material.

A sample of the Galveston beach sand was taken at Sta 134/00, i.e., within the area covered by the two contracts under consideration here. This sample was analyzed for size distribution and the results were as follows:

Size - mm	% Finer than
0.50	99.9
0.25	99.7
0.125	53.2
0.0625	0.3

This is the base material upon which the toe protection was placed and which was to be protected from pumping by a filter blanket.

The D_{15} size of this base material is 0.11 mm and its D_{85} size is 0.14 mm. According to the Terzaghi-Vicksburg standards for selecting a filter material, the D_{15} size of the filter must be between 0.44 mm and 0.70 mm.

Specifications for the filter blanket material on these contracts were as follows (Paragraph 8-04, Exhibit 2a):

Sieve Size	Cumulative % by Wt. Passing % Finer than
3 - inch	100
2 - inch	65 - 100
1 - inch	40 - 70
No. 4	15 - 40
No. 40	0 - 10

Two sieve analyses of material used by the contractor for filter material on these contracts were as follows (Reference 5):

Sieve Size	% Finer than 1-21-61	% Finer than 1-25-61
3 - inch	100	100
2 - inch	89.1	86.4
1 - inch	69.1	67.2
No. 4	31.1	35.3
No. 40	3-6%	3-6%

A comparison of the rating of material used with the job specifications indicate that the contractor met these specifications on the filter material. It is also seen that this material does not have a D_{15} size between 0.44 and 0.70 mm, the actual D_{15} value being about 1.1 mm or about 2 times coarser than required. Furthermore if one examines the range of sizes required by the specifications, it can be shown that a filter material which meets the job specification in the fine size range would not meet requirements for a well designed filter according to the Terzaghi-Vicksburg standards.

As further evidence that the filter blanket was deficient in fine size materials, the Corps of Engineers, Exhibit 2h, in discussing damages at the sea wall in the section east of that covered by the contracts under discussion here made the statement, "In both reaches the concrete blocks were placed on a bedding blanket of smaller stone, but with the difference that the earlier specifications (meaning the Specifications covering area to east of contracts of interest here) allowed more fines in the gradation." A couple of sentences later this same report states, "the older section (meaning that to east) faired somewhat better than the new one."

The actual specifications for filter material on the sections to the east are as follows:

Sieve Size	Cumulative % by Wt. Passing
3 - inch	100
2 - inch	65 - 100
1 - inch	45 - 75
No. 4	25 - 50
No. 40	10 - 25

A comparison of these specifications with those for the sections constructed under the contracts under consideration here, Exhibit 2a, shows at least 10 - 25 per cent of the material had to be finer than the No. 40 sieve (0.42 mm) whereas in the specifications for the newer section only 0 - 10 per cent had to be finer than 0.42 mm.

On the basis of the Terzaghi-Vicksburg standards for the design of a filter blanket in comparison with the grading of the material specified in the contract and used by the contractor, and also on the basis of statements made in Exhibit 2h, we believe there was a deficiency in the design of the toe protection in that its filter blanket was not properly graded.

Consider now the effect of the lowering of the toe protection on overtopping and water going over the top of the sea wall. As previously mentioned in the description of the damage, the toe protection blocks dropped from 1 to 6.5 feet with extensive areas dropping from 3 to 4.5 feet (Exhibit 2k). The first and most obvious effect of the toe protection drop is to increase the still water depth at the sea wall. For example, at the recorded high tide of elevation 9.3 feet and before failure of the toe protection, the still water depth where the toe protection joined the sea wall was 5.2 feet, and at the seaward edge of the toe protection was 6.2 feet. On the other hand with the toe lowered 4 feet, the corresponding still water depths were 9.2 and 10.2 feet.

A comparison of the beach profile where the toe was not severely damaged, Sta. 84/00, Exhibit 2j, with a section where the toe dropped, Sta 101/00, shows that where the toe was undamaged it formed an underwater or submerged barrier about 5 to 6 feet high (i.e. above the beach).

Reference 6 in discussing the work of Dean on fixed barriers in deep water points out that, "submerged barriers are most effective in causing wave breaking and attendant energy losses. The wave reflecting effect is secondary." If the barrier in the case of no toe failure causes waves to break, energy will be dissipated in the shallow water over the submerged toe blocks and therefore the overtopping and runup will be reduced. In those areas where the toe protection dropped, the submerged barrier would be much smaller, the waves would not break, practically no energy would be dissipated, and there would be more overtopping and runup.

Reference 1 reports on model studies on both runup and overtopping. In each case the data are given in terms of deep water waves, that is, $d/L_o > 0.5$. With regards to runup, this reference suggests that the runup is greater when the wave breaks on the structure than when the wave breaks before reaching the structure. Thus, if the toe protection serves as a submerged barrier and causes the waves to break, the height of runup will be reduced.

On pages 90a through 90n, wave overtopping is discussed and data from model tests summarized to serve as a guide in estimating the rate of overtopping expressed as cfs per foot of crest. It is pointed out that these results are influenced by a scale effect in the modeling, but nevertheless, the results should give valid comparisons for different geometric factors. The effect of increased water depth at the toe of the wall is shown by a comparison of Fig. 62E and Fig. 62M. Both of these figures give data for the rate of overtopping of a vertical wall by specified deep water waves as a function of the elevation of the wall crest above the still water level. The results in Fig. 62E are for a water depth at the toe of the wall of 4.5 feet and in Fig. 62M for a corresponding depth of 9 feet. For a wall crest 6 feet above the still water level, which is comparable to the elevation of the Galveston sea wall, and for deep water wave heights of from 6 to 12 feet the overtopping rates range from 0.3 to 0.7 cfs/ft. with a 4.5 foot water depth at the toe of the wall. The comparable rates for a 9 foot water depth at the toe of the wall range from 0.5 to 5.7 cfs/ft. or an increase of 67% for the lower value and 810% for the higher value.

Similar results are given for a curved (Galveston type) sea wall and a water depth at the toe of the wall of 4.5 feet. Comparison with the data for a vertical wall (Fig. 62E) show that overtopping for the curved face of the Galveston type wall is greater than for a vertical wall with the same crest elevation. Corresponding data for the Galveston type wall with a 9 foot water depth at the toe are not shown. However, it is reasonable to expect that rate of overtopping for the Galveston type wall with a 9 foot water depth at the toe would be greater than for a 4.5 foot depth by amounts roughly related to increases shown for the vertical wall.

We know of no way to evaluate precisely the increase in overtopping of the wall that is attributable to the dropping of the toe protection. One of the best tools for evaluating the increase is a hydraulic model. Hydraulic models have been widely and successfully used to investigate complex hydraulic problems. It should be recognized, however, that hydraulic models do not always give exact quantitative answers. In some types of problems, and wave overtopping is one of them, results measured in a model cannot be converted directly into corresponding results for the full scale structure. However, the trends indicated by a model will be applicable to the prototype. When a model is used to investigate breaking waves, as in this case, surface tension forces are important and a significant "scale effect" is present. Surface tension forces, being of greater importance in the model than in the prototype, tend to inhibit the breaking of waves in the model as compared to the prototype. Thus any effect which depends on the breaking of waves will be more pronounced in the prototype than in the model. The scale effect is mentioned in Reference 1, page 89b when discussing runup as follows: "This scale effect results in predictions of wave run-up from small scale tests which are lower than those actually observed."

A 1/24 scale model of the Galveston sea wall was set up in a flume in The University of Texas Hydraulic Laboratory. The beach profile in front of the wall corresponded to that at Sta 84+00 as recorded in Exhibit 2j. This profile was typical of that measured after Hurricane Carla in front of the easterly and older reach of wall where the toe protection had not failed. Blocks in the model could be removed to change this model beach profile to that corresponding to Sta 101+00. The profile at this station was typical of those measured after Hurricane Carla in front of the reach where the toe protection had failed. Waves in the model were produced by a motor driven wave generator with an adjustable frequency and amplitude. The still water depth was set to correspond to the maximum storm tide of elevation 9.3 feet.

In the operation of the model it was reasoned that intermediate amplitude waves were important to an evaluation of the effect of the toe protection on overtopping. The large amplitude, long period waves would break offshore before reaching the wall. The intermediate waves would approach the wall unbroken, but be forced to break by the shallow water where the toe protection remained in place. Where the toe protection failed these waves would not break before striking the wall. When the waves were forced to break as they passed over the toe protection, the resulting loss in energy would decrease the runup and overtopping as compared with similar waves which did not break in those reaches where the toe protection had failed. Small waves would approach the wall unbroken even where the toe protection was in place and consequently would be unaffected by the failure of the toe protection.

The model was operated with different amplitudes of waves. For each amplitude observations were made for a beach profile corresponding to the undamaged reach and also for a profile corresponding to the reach where the damage occurred. The amount of overtopping was measured and the appearance of the waves was observed as they passed over the undamaged and the damaged toe protection. The results of these tests are summarized in the following table.

Results of Model Tests

Beach Profile	Waves	Break on Toe Protection	Overtopping Rate
Sta 84 - Undamaged	Maximum amplitude	Yes	185 ml/15 sec.
	Reduced amplitude	Yes	240 ml/15 sec.
Sta 101 - Damaged	Maximum amplitude	No	640 ml/15 sec.
	Reduced amplitude	No	560 ml/15 sec.

Ratio: $\dfrac{\text{Overtopping rate for damaged reach}}{\text{Overtopping rate for undamaged reach}}$

Maximum amplitude waves	3.5
Reduced amplitude waves	2.4

These model results show that the failure of the toe protection caused the amount of overtopping of the sea wall to be increased to about 300% of the amount for the undamaged wall. This is in agreement with the results on overtopping presented in Reference 1.

Motion pictures were taken to show the nature of the model tests, the wave action, and overtopping at the wall. These movies show that with undamaged toe protection the waves broke before reaching the wall. Overtopping was then less than with the failed toe protection.

V. Conclusions.

As a result of the careful study given this problem, we believe that the following conclusions are justified:

1. The toe protection failed due to a deficiency of fine material in the filter blanket resulting in lowering of the toe protection from 1 to 6.5

feet with extensive areas dropping from 3 to 4.5 feet.

2. The lowering of the toe protection caused an important increase in wave runup and overtopping of the sea wall during Hurricane Carla.

3. The increased overtopping of the wall caused more water to be blown across the roadway and increased the erosion attack on the backfill and the erosion of the sidewalk and roadway areas near the west end of the project.

List of Exhibits

2a. Contract No. DA-41-243-CIVENG-60-70, with specifications, drawings, and modifications, and
Contract No. DA-41-243-CIVENG-60-77, with specifications, drawings, and modifications.

2b. Drawing illustrating status of completion of the structure prior to the storm, being Tab No. M of the Appeal File.

2c1. Eleven drawings illustrating damage to sea wall fill.

2c2. Drawing illustrating repairs made to the structure by Appellant, except for embankment fill behind rear cut-off wall, being Tab No. N of the Appeal File.

2d. Twenty-three photographs showing storm damage to the structure and listed as Tab No. 0-1 through 0-23 in the Appeal File.

2e. Eight photographs depicting status and method of construction generally dealing with toe protection on dates indicated in captions underneath each one, on Contracts 60-70 and 60-77.

2f. Nineteen photographs depicting status and method of construction generally dealing with toe protection and embankment on dates indicated in captions underneath each one, on Contract No. DA-41-243-CIVENG-58-149 and Contract No. DA-41-243-CIVENG-59-127, such contracts being for construction of seawall between Stations 54+00 to 74+00.

2g. Movie film showing wave action in early stages of the storm and damages by Hurricane Carla to various portions of entire Galveston seawall structure.

2h. Report on Hurricane Carla dated January, 1962, and prepared by the U. S. Army Engineer District, Corps of Engineers, Galveston, Texas.

2i. Weather data compiled by the U. S. Weather Bureau Office, Galveston, Texas, and titled, Hourly Meteorological Data, Hurricane Carla, September 9 thru 12, 1961.

2j. Beach cross-sections of the Galveston beach showing after Hurricane Carla conditions, consisting of twenty-one sheets and having been prepared by William-Stackhouse and Associates under Contract No. DA-41-243-CIVENG-62-75, pursuant to investigation being made between 6 October 1961 and 19 November 1961.

2k. Toe protection profiles of portion of Galveston seawall, consisting of two sheets, from Stations 54+00 to 163+ 85 based on information obtained October and November 1961 for the toe protection, and May 1962 for sand indicated thereon.

References

1. "Shore Protection Planning and Design", Tech. Rep. No. 4, Beach Erosion Board, 1961.

2. "Soil Mechanics in Engineering Practice", K. Terzaghi and R. Peck, John Wiley and Sons, Inc., New York, 1948.

3. "Investigation of Filter Requirements for Underdrains", Tech. Memo. 183-1, U. S. Waterways Experiment Station, Vicksburg, Miss., December 1941.

4. "Laboratory Investigation of Filters for Enid and Grenada Dams", Tech. Memo. 3-245, U. S. Waterways Experiment Station, Vicksburg, Miss., January 1948.

5. Correspondence with Thorstenberg Materials Company, Inc., October 25, 1953.

6. "Estuary and Coastline Hydrodynamics", Hydrodynamics Laboratory, Massachusetts Institute of Technology, 1963.