https://doi.org/10.26749/rstpp.102.11

PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA, VOLUME 102

WAVE TANK EXPERIMENTS ON THE EROSION OF ROCKY COASTS

By

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(With three text figures and one plate)

ABSTRACT

Erodable blocks representing vertical cliffs and shore platforms were exposed to attack by artificially generated waves. Maximum erosion in all blocks occurred above still water level. Vertical cliffs became deeply notched in a form which contained no horizontal portion and which had the lower segment located below still water level. Platform shapes were degraded by cutting on the platform surface and rounding of the leading edge. No wave-tank evidence was found to support the contention that high tide shore platforms are presently being formed by storm wave activity. Notches on the sides of the blocks were caused by acceleration of waves constricted between the block and tank sides. Such constriction and attendant increase in velocity may also favour rapid erosion in sea arches, caves and closely spaced stacks. Erosion debris moved rapidly from the base of the model cliff and was not involved in subsequent block notching.

INTRODUCTION

Hydraulic activity and various forms of mechanical and chemical weathering operate simultaneously in shaping rocky coastlines. Complexity of factors makes the isolation of any one aspect, such as hydraulic phenomena, very difficult in the field. Consequently, a model study was undertaken to gain an insight into the erosion forms resulting from hydraulic action alone. The method involved the direction of artificially produced waves of known characteristics against an erodable block representing a sea cliff. Experiments were conducted over a period of several months in a wave tank assembled for the purpose.

CONSTRUCTION OF WAVE TANK

Construction of the wave tank was simplified by the generous loan of a flume by the Engineering Department at the University of Tasmania. The flume, normally used for experiments in hydraulic flow, consisted of a tank with perspex sides of 9′ 6″ length, 8″ width and 16½″ height. It was only necessary to seal the flume at both ends in order to use it as a wave tank. The remaining construction work consisted principally of producing a paddle and driving arrangement to generate waves. The chief difficulty was that no alteration could be made to the existing flume and the paddle and drive units were fabricated to meet this requirement.

Out of the many different ways of making waves, it was decided to utilize a paddle pivoting on hinges fastened to a block at the bottom of the tank. The paddle was driven by a rod attached to a plywood disc by means of a nylon bushing turning on a stainless steel bolt. The bolt could be adjusted in a slot to vary the length of throw and hence the wave amplitude. The disc was driven by a stainless steel shaft on which was mounted a four-sheave V-belt pulley. Power for the V-belt was provided by a reduction box turned by an ⅛ h.p. electric motor. A variation in the period of the waves was attainable by moving the V-belt from one sheave to another.

The simulated offshore profiles offered minor difficulties. No holes could be drilled in the bottom of the wave tank for securing an adjustable profile ramp. Consequently it was necessary to use a gravel bed to form the required slopes. Gravel was placed in the tank and a steel plate laid on the surface to simulate an offshore profile. The plate was positioned by scooping gravel from one location to another until the desired profile was obtained. The gravel also served to hold the erodable blocks upright and in this capacity fixed the blocks securely enough to avoid movement upon wave impact. Wave reflection posed another problem. However, the reflections were reduced to an acceptable level by placing rubber-covered horsehair pads in both ends of the tank.

BLOCK CASTING

Production of the model cliffs themselves followed completion of the tank. A block was needed which was firm enough to stand unsupported in the water but incompetent enough to erode in this small-wave environment in a reasonable time. The first block contained a mixture of one part of mortar to 70 parts of sand. This mixture had been used successfully by the Tasmanian Hydro-Electric Commission hydraulics laboratory in model spillway erosion tests, but the block proved to be too weak to stand by itself in the tank when wet.

The second attempt utilized a stronger mortar mix; one part mortar to 35 parts sand. This block stood competently in the tank, even when wet, but was practically unerodable. It seemed evident that somewhere between a ratio of 1:70 and 1:35 would be found a mixture which would stand in the tank and also erode easily. However, the time necessary to mix and cure the mortar (on the order of four days) indicated that another type of block would be more advantageous.

A suggestion was made to try plaster mixtures and a number of samples were prepared. A mixture of 50% plaster and 50% fine grained quartz sand resulted in a block which was much too hard. A mix of 25% plaster to 75% quartz sand was softer and more erodable, although the erosion rate was still fairly slow. The next block had a composition of 15% plaster to 85% quartz sand which had better erosion properties. A block composed of 10% plaster and 90% quartz sand was difficult to handle without breaking, but yielded rapid erosion. The final test mixture of 5% plaster to 95% quartz sand was extremely fragile and tended to crumble upon water contact.

A block containing 25% plaster and 75% sand was prepared and placed in the tank for the first run. This block and subsequent models were cast in the same mould and had dimensions of 16¾" x 5¼" x 2¾". The block was installed in the tank with its broad dimension (5¼") facing the oncoming waves. Distance from block face to wave generating paddle was six feet, a dimension which was held constant for all the plaster block experiments.

BOTTOM PROFILE AND WAVE CHARACTERISTICS

With the block in place it was necessary to establish profile and wave characteristics. An offshore profile was needed which would produce properly breaking waves in the tank as well as simulate conditions found in the field. A deep profile, in which the depth of the shallow end was more than 1.25 of the wave amplitude, would create a reflective clapotis situation. A very shallow profile, on the other hand, would result in complete waves of translation. In this small tank proper water return for a complete wave of translation was not possible. In addition, many rocky coasts are fronted by depths of water sufficient to prevent waves from breaking completely. A profile depth was finally chosen which would yield a partial wave of translation superimposed upon a wave of oscillation. The steel plate which established the profile was placed 2¼" below still water level at the cliff face and 4½" below the datum at a distance 24" from the block. The gravel bed under the plate sloped abruptly to the tank bottom at this point.

Wave characteristics were established to be compatible with the selected profile. Deep water wave height was $3\frac{3}{16}$" and wave length was 19½". Thus the waves were oversteepened, with a value of 0.164, which would be similar to natural conditions in a storm. Wave period was 0.652 seconds. These parameters yielded a wave which started to break about 14" from the block face and which had broken through half of its height when it struck the vertical surface. Upon reaching the block, the total height of the broken wave between crest and trough had decreased to $2\frac{3}{8}$" from the unbroken amplitude of $3\frac{3}{16}$".

OPERATION

The tank was filled and wave paddle activated for run number P1 when the preparations were complete. The block was observed closely during this initial period for any signs of erosion. Within 20 minutes sand grains could be detected by feel on the previously smooth front face of the plaster-sand model. Water was shooting up the face to a height of six inches above still water level, but no visible notch was present. In the first hour of operation numerous pits, having an average diameter of about $\frac{1}{16}$", formed on the face. After four hours of continuous operation the pits had enlarged until a few had reached $\frac{3}{32}$" in diameter. A notch of $\frac{1}{32}$" average depth had formed on the face, in addition to other notches on the sides of the block. The side notches apparently resulted from the speeding up of the water movement as the breaking waves became constricted between the block and the tank sides. As the experiment progressed, the notches deepened through coalescence of the numerous pits. The paddle was stopped after a running time of 18 hours and 22 minutes at which point the block had spent a total of 31 hours and 47 minutes in the water. A profile was obtained by a tedious proces of cutting and recutting a cardboard template until template and block surface matched. In order to avoid possible errors through inclusion of the side notches in the frontal

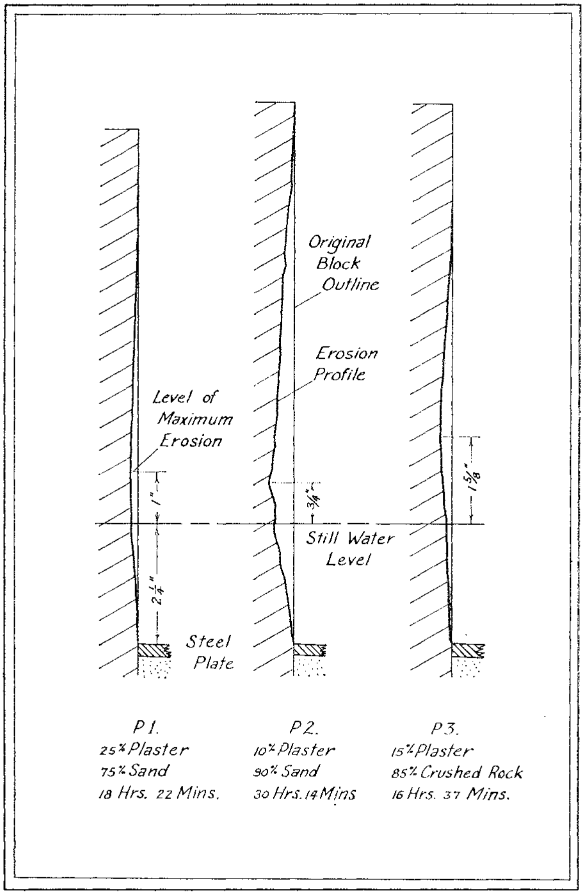

FIG. 1.—Erosion profiles of vertical cliff model Nos. **P1**, **P2** and P3.

profile, the template was cut in the center of the block face. The profile resulting from this experiment is shown in Figure 1.

Another block was prepared with a mixture of 10% plaster to 90% quartz sand. This weaker mixture was intended to hasten the erosion process in order to get a better insight into the notching mechanism. Wave characteristics and the offshore profile were as identical as possible to Run P1. The rate of erosion proved to be greater on the new block, but the other characteristics remained the same. Sand grains were first evident on the face, followed by pitting, grooving and notching. Block P2 was eroded for 30 hours and 14 minutes before being removed from the tank. In contrast to run P1, Run P2 was continuous, with the immersion time equalling the running time. Block P2 showed a profile with greater depth and more irregularity than P1.

The third run, P3, was made with a plaster and crushed dolerite mixture. This was an attempt to simulate a natural condition in which jointing and bedding would be present. Crushed dolerite held in a matrix of plaster would furnish a coarser texture upon which the hydraulic action could work. The block was composed of 15% plaster and 85% crushed dolerite with an average diameter of ⅛″. This mixture was mechanically sound and yielded a block which suffered no crumbling in water and eroded satisfactorily. The offshore profile and wave conditions were identical to previous runs. The surface pitted rapidly on the new block and the material appeared more permeable. The notching continued as usual on the face, but exceptionally rapid erosion took place on the side of the block. Apparently the mixture was not uniform and the side of the block was less well cemented than the front. Throughout this run the side notch continued to cut across the face, with a greater cutting rate than on the front. The side notch cut higher as it neared the center of the block and also undercut the face notch to a depth of about ¾″. The experiment was allowed to continue for 16 hours and 37 minutes over a period of two days and one night. The tank was drained during the time it was not in operation. In general the frontal profile attained is very similar to those of the plaster and sand blocks, except that the level of maximum erosion is higher (Figure 1).

Run P4 was an ill-fated experiment with a very rapidly eroding mixture. A block was produced which was 5% plaster and 95% quartz sand. The block started to crumble as the tank was being filled and was cracked even before installation. The top half of the block was held in place by hand and wave generation initiated. Erosion was rapid, especially laterally about ¾″ behind the face. Before the block collapsed completely in about three to four minutes, a 1″ notch had been produced on the struck face. Erosion was very rapid indeed but the block was mechanically too weak to stand in the tank.

Run P5 was conducted with a block which was 15% plaster and 85% quartz sand, cast in a platform shape. Unfortunately, before the block was placed in the tank the top half broke from the bottom section, leaving a joint where the two pieces fitted together. The block was set in the tank in spite of the fracture to allow experimentation to continue while a new block was being cast. The top section was clamped to a wooden support which braced the model sufficiently to withstand wave impact. As in the previous plaster blocks sand grains were detectable within a few minutes and pitting, grooving and notching followed. The notching, however, was of a different nature than in previous runs due to the platform configuration of the model. Cutting during Run P5 occurred in three separate areas: the leading edge of the platform, the platform surface and the cliff face. Considerable erosion also took place along the fracture at the base of the cliff.

After three hours of operation, the leading edge of the platform was rounded to a half-inch radius and notching was very apparent at the rear of the platform. Waves of translation were rolling across the platform and were deflected both upward and downward by the cliff. The waves that were deflected upward were removing material to a height of two to three inches above the platform surface and the portion of the wave which was deflected downward appeared to be scouring a notch in the platform surface itself, as well as into the base of the cliff.

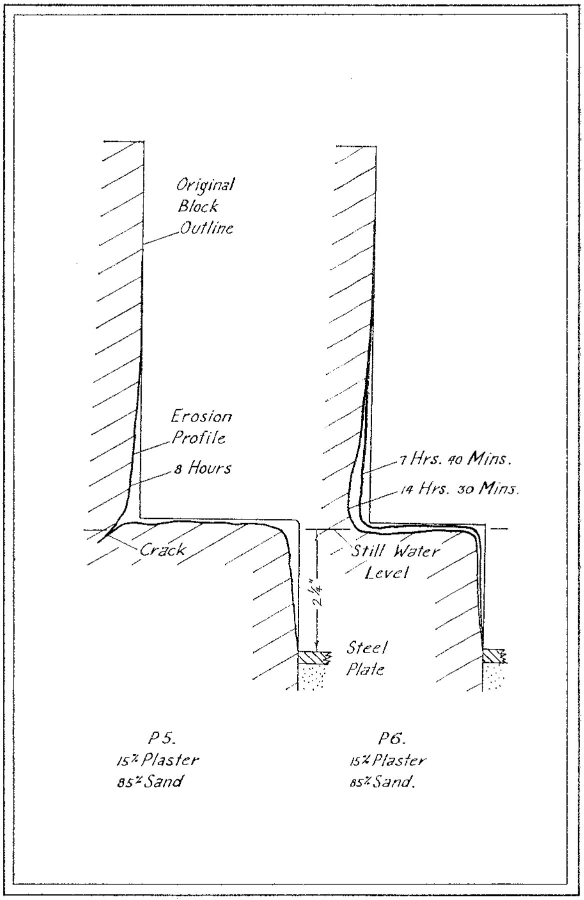

FIG. 2.—Erosion profiles of platform models Nos. P5 and P6.

The tank was drained after three hours and re-started on the following day. However, the tank was allowed to run for only five more hours before the final draining. The erosion patterns being created in this platform-shaped block warranted further study, but the top of the block was becoming insecure and it was necessary to stop. The profile attained during this eight-hour experiment is shown in Figure 2.

Another platform block was shaped in order to ascertain if the notching on the P5 platform surface was related to jointing in the broken block. The new block, P6, was also a 15%-85% plaster-sand mixture, but the platform profile was cut with a hacksaw instead of being cast in place as in the previous experiment. Cutting produced a markedly improved profile over that obtained by casting. Edges were completely square on the cut profile, while some rounding was inevitable with the casting technique.

The block was set in place, as previously, with the platform surface about ⅛" above still water level. Shortly after starting the experiment the usual pitting and grooving occurred, becoming most pronounced at the rear of the platform. A notch cutting into the rear of the platform surface became evident after about two hours of operation. Erosion continued in this area throughout the 14 hour and 30 minute run, indicating that notching into the rear of the platform was not caused by the jointing in block P5. The final profile (Figure 2) shows deep cutting into the platform surface, leaving the leading edge area standing as almost a " rampart ".

Blocks Nos. 5 and 6, in contrast to earlier models, had been placed in the tank with their narrow dimension facing the oncoming waves. The new position had the effect of reducing the reflected waves, and changing the standing wave condition in the tank to allow a purer incoming wave form. Some experimentation appeared necessary to determine the type of notching which would occur in a straight faced block (instead of a platform shape) inserted in this manner. Therefore, another plaster block was cast with a 15% plaster to 85% sand mixture.

The new block, No. P7, was installed in the tank and allowed to erode for a total time of 30 hours and 45 minutes over a three-day period, during which the tank was drained when not in operation. The results indicated that a similarity does exist in the notching forms of this block and the blocks with their broad dimension facing the waves. In both cases the maximum frontal notch development showed a good height correspondence with the portion of the wave which had broken (Figure 3). The greatest notching occurred between the level of the broken wave crest and the base of the turbulent zone. As the base of the turbulent zone was about halfway between the wave crest and the wave trough, maximum notching took place in the area struck by the upper half of the wave. Further examination of this phenomenon would have been useful, but the Engineering Department required the flume at this time for its own studies.

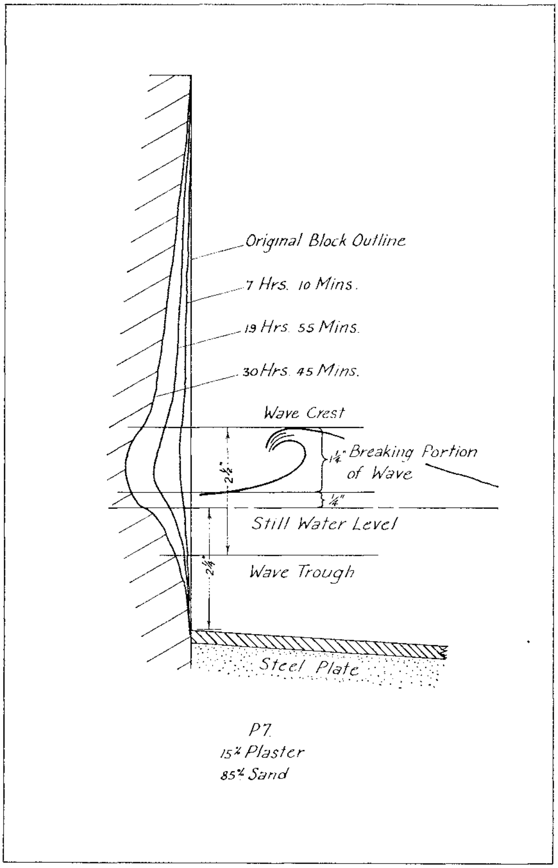

FIG. 3.—Erosion profile of vertical cliff model No. P7, showing relationship between erosion and breaking waves.

ANALYSIS OF RESULTS

The wave tank experiments indicated several characteristics of hydraulic action in a model coastal environment. The first aspect was the occurrence, in all blocks, of the maximum erosion at an elevation above still water level. A similar situation has been noted by engineers measuring the intensities of pressures created by waves breaking against upright surfaces in the shore zone. Two factors are involved in this phenomenon: (1) The entire wave form is shifted upward when decreasing depths are encountered (Plate 1, Figure 1) and (2) The upper part of the wave produces the highest pressures upon breaking. Bagnold (1939), in his wave tank experiments on the pressures produced by breaking waves on vertical walls, found maximum shock pressures between the wave crest and 0.6 H above the wave trough. The waves used were of 10-inch amplitude and had been displaced four inches upward in relation to still water level during progress up an incline before striking the wall.

Although conditions in the present experiment were not identical to Bagnold's, a general correlation between the zones of highest shock pressure and greatest erosion exists. On Block P7, a breaking wave 2⅜″ high repeatedly struck the vertical face. In contrast to Bagnold's wave, this wave was displaced only 0.1 of its total height above still water level. The maximum erosion was centered in the upper half of the wave, ¾″ below the crest (Plate 1, Figure 2). Inflection points between the concave curve of the zone of maximum erosion and the convex curve in adjacent areas occurred at the top of the breaking wave and at still water level. The zone of maximum erosion is thus extended further downward than Bagnold's maximum pressure area. Two reasons for the difference may be that wave and bottom characteristics are not identical and that Bagnold was measuring only shock pressures, while the plaster block cliff was reacting to wave shock combined with other activities associated with moving, turbulent water.

Other phenomena appeared when platform shapes were exposed to wave attack. A notch formed in the cliff face as expected, but cutting also occurred on the platform surface, especially at the rear. Cutting on the surface degraded the horizontality to a point where the horizontal plane of the platform had disappeared by the end of the experiment. The tendency for hydraulic action to establish smooth curves whenever possible became very apparent. Angular junctions of the surfaces at both front and rear of the platform were rounded into shapes approaching the elliptical " ogee curve " which offers least resistance to flow.

GENERAL CONCLUSIONS

Difficulty is always encountered when the attempt is made to relate a model study to the full-scale environment. The only thing that such a study really shows is that model waves of certain characteristics striking plaster-sand cliffs have a particular effect. For this reason no detailed analysis of the individual profiles was made, and only general conclusions were drawn. These general results, however, may be applicable in the real environment.

Workers in the field of shore platform study have stated that the greatest " storm wave " erosion would take place above mean sea level and these experiments suggest that this opinion may be correct. Bartrum (1924) typified this view when he ascribed platforms two feet above mean high water level to storm wave activity, acting on " homogeneous and resistant " rock. This concept has also been voiced by Jutson (1939) and other, more recent authors.

While the experiments support the contention that erosion is greatest at elevations above mean sea level, they fail to provide evidence that platforms may be produced by hydraulic action alone in a homogeneous, un-bedded and un-jointed material. Wave activity on the vertical model cliffs produced a rounded form with a deep notch and little horizontality. The lower half of the notch contained no horizontal component and was located below still water level. In addition, the pre-existing horizontality on the platform models was badly degraded by wave attack. If rounded notches with bases below mean sea level are produced in a similar manner by wave action in the real environment, some additional processes involving mechanical and chemical weathering will be required for the formation of level, elevated surfaces in many coastal rocks.

The notches created by accelerated flow along the sides of the blocks may also have full scale analogues. Formation of these notches, often as deep or deeper than the frontal depressions, may be related to the production of sea caves, arches and stacks. As the waves in the model study funnelled between the plaster-sand blocks and the tank walls, the water velocity was locally increased. The resulting pattern of erosion showed the greatest vertical dimension of the notch at the point nearest the wave source, but the maximum horizontal cutting at a point further towards the rear of the block where velocity was greatest. The relatively rapid erosion of arches and closely spaced stacks may be due to a similar increase in water velocity as wave energy becomes concentrated in narrow channels.

Another phenomenon which might have significance in the real environment was the behaviour of the material removed from the eroding blocks. The material was immediately swept away from the rock face and deposited in a break-point bar and a series of small ridges offshore. At no time was there a tendency for material to pile up at the base of the cliff as suggested by Cotton (1945). Cotton wrote that wave attack on a steep coast would not produce notching until sufficient talus had accumulated at the cliff base to act as cutting tools. The present experiments suggest that the talus would probably be transported offshore until a tremendous mass had accumulated and that erosion by unarmed hydraulic activity would have taken place in the interim.

Much more information could be derived from further wave tank experiments on erodable blocks. Throughout the present experiments, the wave characteristics and off-shore profile were kept as identical as possible from run to run. Interesting data might result from noting variations in erosion patterns as these parameters were changed. Experiments on multi-layered blocks containing differently resistant material would also be worthwhile, as would additional studies on jointed blocks. Finally, further refinement of method could add more quantitative information to the qualitative data already received, although scaling these occurrences in terms of material, time, size and distance would be difficult.

ACKNOWLEDGMENTS

I am indebted to Dr J. L. Davies of the University of Tasmania for helpful comments and advice. I would also like to thank Professor A. R. Oliver of the University of Tasmania, Engineering Department, for the use of his equipment and Mr W. F. Navin and the staff of the Hydro-Electric Commission Hydraulics Laboratory for their assistance

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PLATE 1

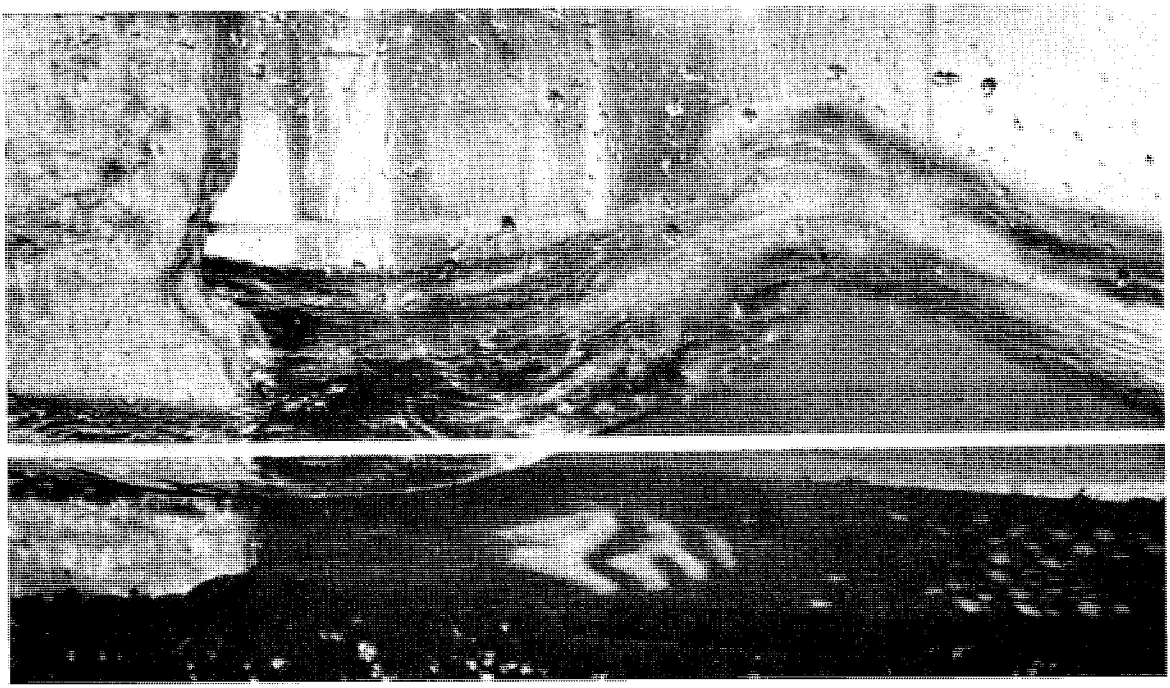

FIG. 1.—Model wave just after breaking, oblique view. The wave form has been displaced upward with respect to still water level (represented by the top edges of the horizontal white lines on both sides of the tank). The block, No. P7, shows deep side and front notches and well developed pits. Eroded block material has accumulated offshore from the block on the steel profile plate.

FIG. 2.—Model wave striking block, oblique view. Broken portion of wave neatly fits into notch created by wave action. Greatest depth of notch is about ¾″ below wave crest at striking. Part of the wave has already passed the block and is being channelled between the block and the tank walls.