# THE BEHAVIOUR OF PROTOTYPE BOULDER REVETMENT WALLS

By A.W. Smith * & D.M. Chapman **

## 1. Introduction

This paper reports the results of on-site observations of coastal revetment structures under extreme storm conditions on the Gold Coast of Australia. The Gold Coast is located at approximately Lat. 27° S on the East Coast of Australia facing the Tasman sea behind a narrow continental shelf and exposed to a relatively high energy wave climate as depicted in Fig 1. Tropical cyclones generate the highest storm activity on the Gold Coast with Ho values commonly exceeding 10m with the resultant onshore wave i.e. either the second or third wave reformed breaks within the range of 2.5 to 3.5m. Storm wave periods are usually between 8 to 18 seconds. The ocean beach on the Gold Coast, some 30km long has been receding since the early forties and this has resulted in the construction of nearly 20km of revetment walls to "protect" the rear beach. Whilst some walls in particularly erosion-prone areas were constructed in the 1920 decade, most have been constructed since 1967 which represented a particularly high cyclone prone year. Since the latter period the walls have been exposed to three further periods of high cyclone energy attack in 1972, 1974 and 1976. Nearly all revetment walls demonstrated at least some settlement and damage but over the three storm periods at least 0.8km of wall was completely destroyed. Most wall failures were monitored on site and whilst the construction of the walls varied in quality the observational results might well be classified as full scale prototype performance tests.

## 2. Boulder Walls

Over 90% of all Gold Coast revetments are boulder walls constructed from natural stone with a filter layer of well weathered quarry overburden material that effectively consists of a natural mixture of weathered gravel and clay.. All boulder revetments are founded at Mean Sea Level because below this the beach resists excavation by going "quick" and cofferdamming costs are prohibitive. Local philosophy has always been to found walls at M.S.L. and merely top them up in response to settlement and storm damage. The typical form of Gold Coast boulder walls is shown in Fig 2(a) and the official design standard in Fig 12(a).

The collapse mode of boulder walls is set out diagrammatically in Fig 2 starting with the as-built wall and finishing with the wall completely vanished and buried beneath the eroded beach profile. The initial failure has always been triggered by subsidence of the toe, this has then caused the face armour to rattle down until the wall's freeboard has been reduced enough to allow overtopping. As soon as the overtopping has become practically continuous the erosion of filter material became extremely rapid with the rump of the wall finally collapsing landwards into the

* Gold Coast, Queensland, Australia
** University of Sydney, Australia

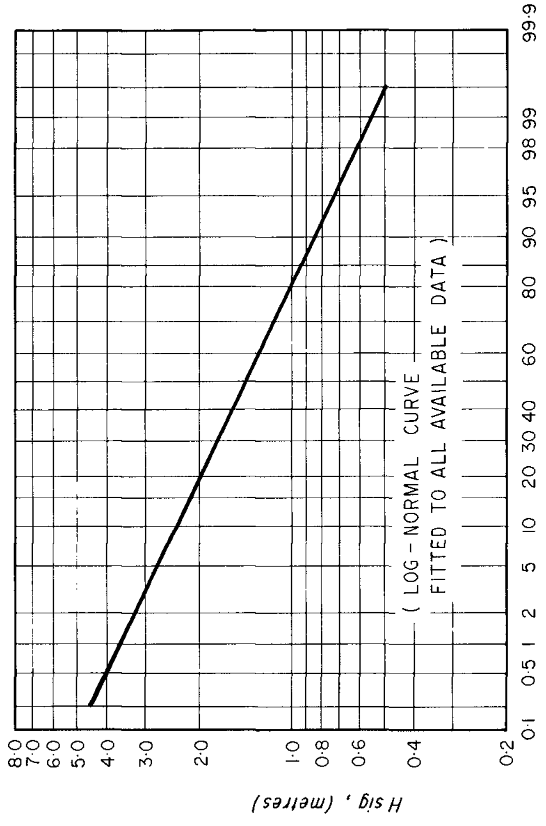



FIG.1 WAVE HEIGHTS , GOLD COAST
PROBABILITY of EXCEEDANCE

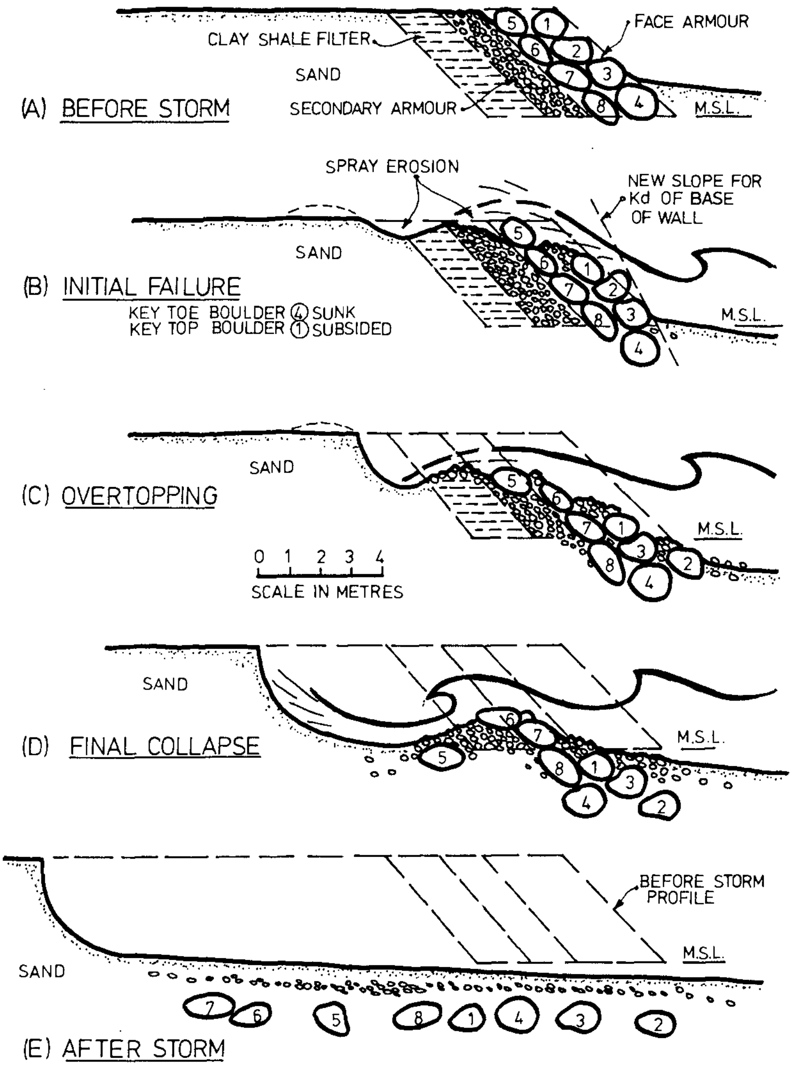



FIGURE 2:— COLLAPSE MODE OF BOULDER REVETMENT.

eroded space. The full sequence of events as shown has been observed to occur within less than 20 minutes for walls over 5m. high. The initial step by step and final positions of the numbered boulders shown in Fig 2 is typical of observed wall collapses, but it is naturally not universal, the shapes of boulders provide highly variable interlocking, some boulders bounce out of the wall during the rattle-down sequence, and small boulders (particularly in position 5) are readily plucked off the top of the wall and rolled landwards.

The initiation of toe failure has always followed the generation of semi-fluid or quicksand conditions in the beach under the toe as the lower end of the wave's trailing edge passes this zone. Once the sand becomes periodically fluidised the very low specific surface of the boulders ensures that they sink very rapidly step by step under each wave. Five tonne boulders have been observed to completely disappear in less than 150 seconds, or only 8 to 10 waves. Back-wash scour is not the mechanism of boulder settlement, as the filter layer erodes and the wall ruptures, overtopping generates a full work prism in the sand under the wall and the wall debris settles within the fluidised zone in proportion to the particle specific surface as shown in Fig 2(e) and confirmed by subsequent excavation of the beach. It might thus be observed that the practice of testing revetment walls of the class herein reported in "hard-bottom" flumes, i.e. without a sand underlay would be unlikely to reproduce the observed collapse mode of these prototypes.

From Fig 2(b) it may be noted that as the toe of the wall subsides the slope of the near toe boulders increases, thus the stability of the wall i.e. its Kd value decreases. Continued wave attack may then extend wall damage at an increasing rate, even with a constant or declining wave energy input.

## 3. The Role of Key Boulders

As can be seen from Fig 2 the two key elements of wall stability are the leading toe boulder (No. 4 in the diagram) and the top face boulder (No. 1 in the diagram). If neither of these boulders move the wall may maintain a capacity to resist in the short term very high hydraulic overloads.

Early efforts locally to increase the stability of the toe led to the use of the largest boulders as the key toe units. This approach was a complete failure, the bigger boulders had a lower specific surface and thus sank into the fluidised beach more easily and more quickly than standard boulders. Indeed some very large toe units sank into the beach during comparatively mild wave conditions and the walls supported by them had become dislocated before the arrival of the first storm. An alternative approach of bedding the toe boulders on secondary armour and filter material has to date also been only partially effective, since toe stability cannot be assured until the key toe unit is founded at the bottom of the work prism fluidised during a storm. Without the expedient of cofferdamming therefore it has had to be accepted that the full design capacity of the local walls cannot be attained until they have been "tempered" by one or several storm attacks and the walls topped up to accommodate the essential toe settlement.

The use of heavier boulders for the key top units has, however, proven rather more successful. In order for the key top unit to hold a Kd value equal to the other face units it should be larger in any case, the top boulder has no gravity surcharge and the least interlocking with its neighbours. It is thus the unit most susceptible to uprush and backwash forces. It is difficult however to place large top boulders flush with their surrounding armour, their size alone tends to result in them standing proud of their neighbours and leaving large gaps in between them. In this position they are very prone to rolling landwards under wave uprush and in one case a 15 tonne key unit was rolled 4 metres inland by an overtopping rush of white water only about a metre deep. The best solution seems to lie in using the largest high aspect boulders available laid flat in the top zone of the wall with their smallest face exposed to the sea and extend the top of the wall with extra top armour as shown in Fig 12(b).

An extremely effective expedient adopted on the Gold Coast for existing walls during high storm activity has been the provision of temporary top armour in the form of a single layer of sandbags laid flat and touching as shown in Fig 3. Such temporary armour however must be continually maintained by manual replacement and repair as it becomes damaged and as it distorts in response to settlement of the wall.

4. Timber Walls

At various times many segments of timber seawalls have existed on the Gold Coast with the earliest constructed circa 1920. All however have failed at one time or another and been replaced or faced seawards with boulder walls. The failure mode of a typical timber wall as shown in Fig. 4 is characterised by initial toe scour and undercutting accellerated by a lack of filter backing and the inability of the wall to settle. After a storm the partial skeleton of a timber wall may usually be seen well seaward of the erosion scarp it has failed to halt and the only reinforced masonry block wall constructed locally suffered the same fate in the same manner.

5. Grouted Walls

At one stage grouted walls became quite popular on the Gold Coast, these walls consisted of ordinary boulder walls where the Owner placed concrete in the voids between the rocks. The storm performance of these walls however has been very poor and they have always failed more rapidly than the standard walls. Ordinary face boulders absorb a great deal of wave energy by rocking and impacting on their neighbours; all boulder walls can be heard to "growl" under heavy wave attack and vibrations and movements within the armour can be felt by merely standing on top of them. Grouted armour cannot respond in this manner and the smoother more impervious face of grouted walls results in much larger uprush and overtopping volumes which lead to extensive early soil erosion behind them. It is practically impossible to effectively grout boulders in a semi submerged toe zone so once toe failure is initiated and the toe boulders settle the mass of the wall is left suspended until it collapses in a single shattering event as shown in Fig 5.

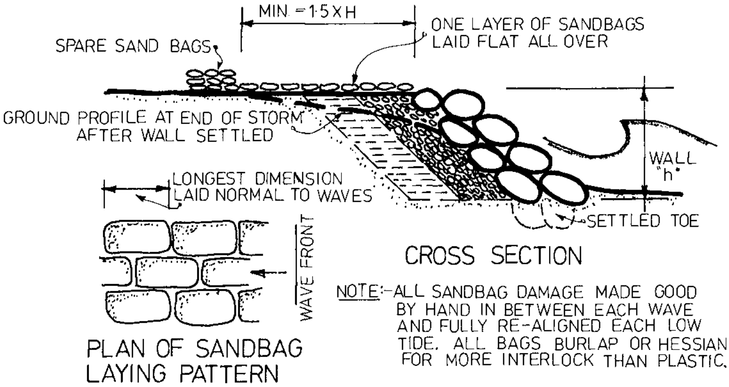



FIGURE 3:- GOLD COAST TEMPORARY TOP ARMOUR FOR REVETMENT WALLS.

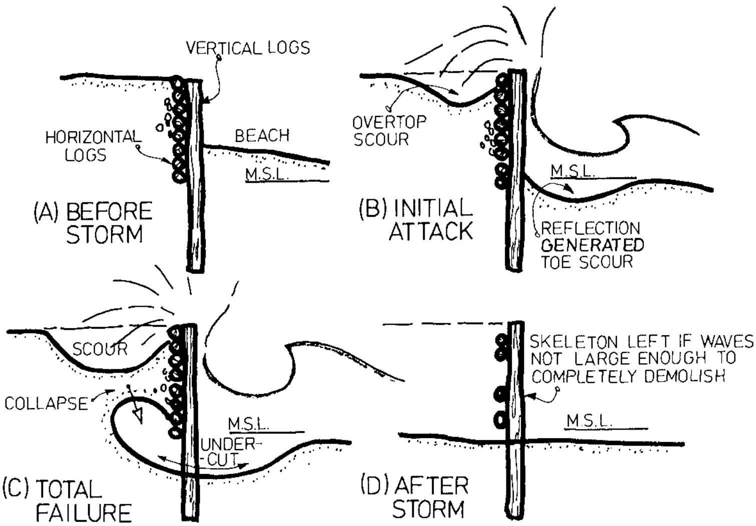



FIGURE 4:- FAILURE MODE OF LOG WALL

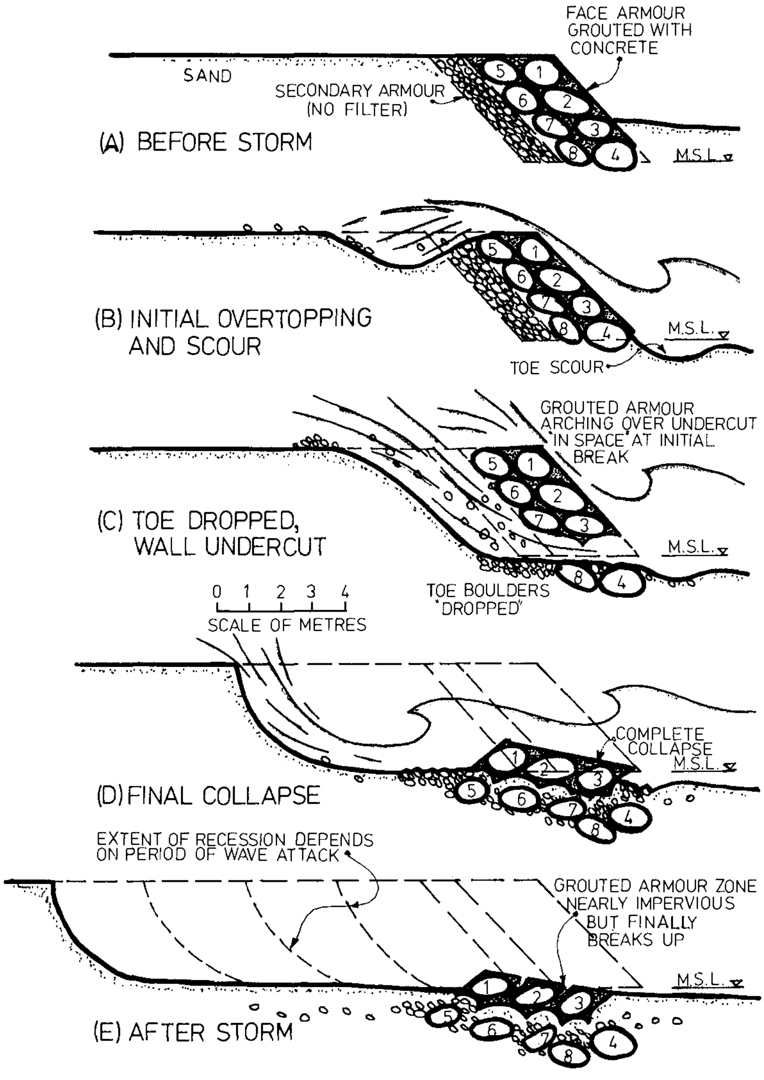



FIGURE 5:- COLLAPSE MODE OF GROUTED WALL

6. Double Waves

Of all the natural phenomena that may be included in a tropical cyclone event on the Gold Coast, the most frightening by far is the development of double waves. At least three times, in 1967, 1972 and 1974 during major storms this phenomenon has generated at least one short train of super waves, usually limited to four but sometimes reaching six in number. During a lull or low period in the incoming wave train the beach immediately in front of the revetment wall has been left nearly "dry", but this lull has been followed by a sequence of relatively large long period waves. The celerity of the first of these waves is retarded as it runs up the beach as a bore, usualy only some 2 metres deep; but the next waves celerity is not affected so it runs over the top to produce a double wave with a combined amplitude which may reach 5 metres and sometimes much more. Once the first double wave is generated the next three or four waves then also ride over the local high set-up which has been formed and the doubling phenomenon continues until the temporary set-up initiated by the first wave double drains away, and a normal wave train is re-established.

Such double waves however can do immense damage. On natural beaches such waves may overtop the highest dunes and as been observed, cause nearly seven metres recession of an erosion scarp for each double in a train. They also overtop local revetment walls with nearly two metres of green water, smashing into houses and washing away cars and other movable objects. On the Gold Coast their frequency to date has been about three major wave doubles on the beach per 8000 deep water peak storm waves per storm event but their probability remains unknown. Locally the phenomenon occurs often enough however to ensure that it will be inevitable that all revetment walls during their life-time must and will be exposed somewhere to very massive overtopping. Fortunately this process has always tended to be localised, the maximum length of beach observed affected has not exceeded a kilometer and has usually been only a third of this. Double waves can, and do, pop 5 tonne boulders out of revetment walls like champagne corks, a sight never to be forgotten once seen.

7. Gravity Forces

In the design of coastal structures it is easy to proportion the armour size and geometry for wave resistance properties alone. In addition to absorbing wave energy these structures must also maintain the capacity to hold themselves up; clearly any structure which is at its limit under body, or gravity forces alone, cannot be expected to hold any useful reserve to accept additional hydraulic forces. The local boulder revetments constructed at a slope of $1\frac{1}{2}$:1 have a factor of safety under gravity of only 1.06, a very sobering thought. It would not be surprising that for any sea wall near to its own self weight capacity, then the first element to fail should be the leading edge toe boulders, they are the most heavily stressed of all. Any seabed toe liquifaction can then only guarantee an initial failure and settlement.

8. Wave Set-Up Surge

Most coastal design texts e.g. the S.P.M. (C.E.R.C., 1977) provide ample tools for estimating surge levels due to barometric drop and wind set-up but the estimation of a realistic wave set-up appears to be a rather more

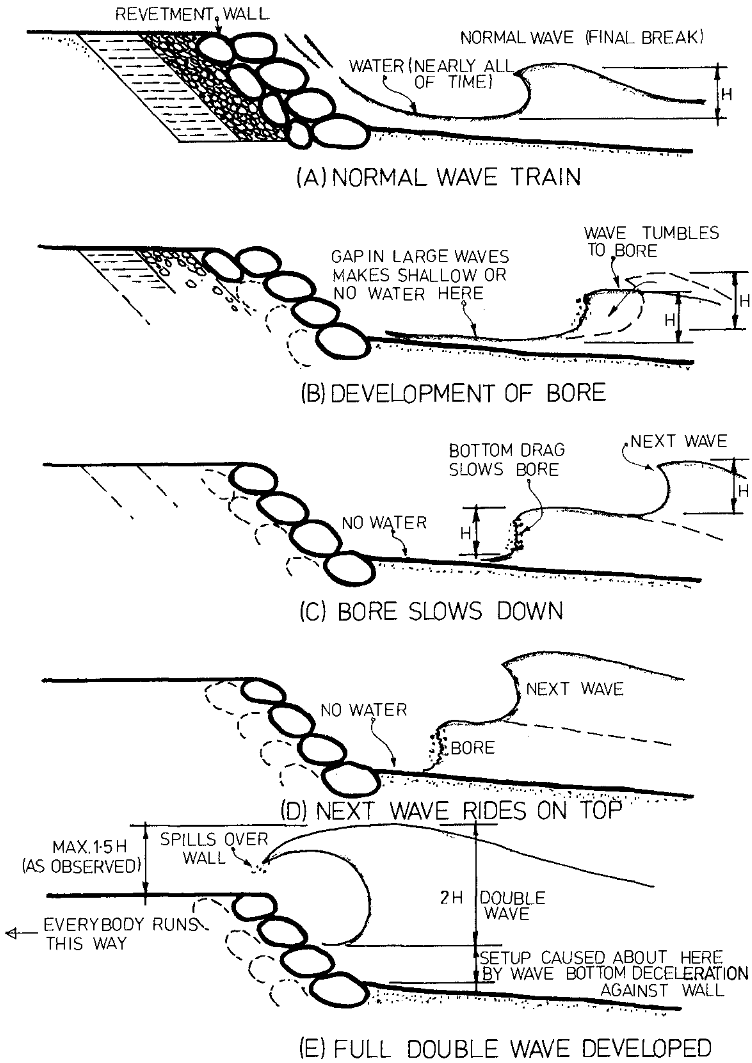



FIGURE 6:– DEVELOPMENT OF DOUBLE WAVES

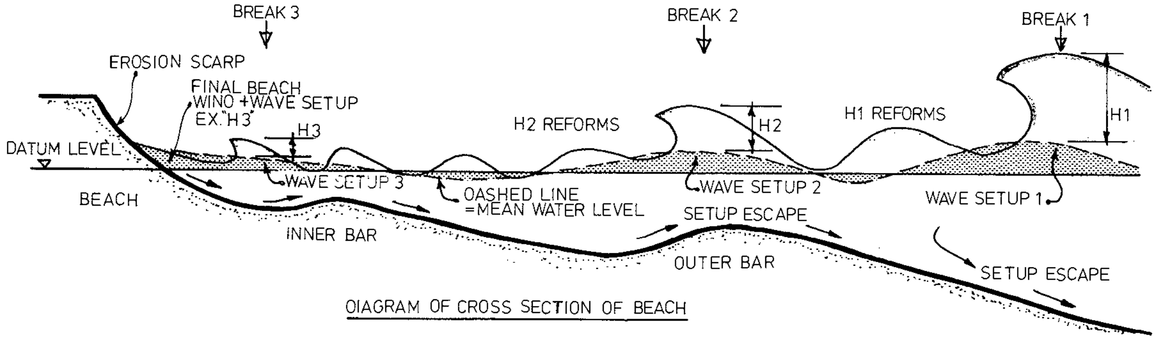
intractable problem.

On the local coast during storm wave trains with Hsig exceeding 7 metre there are at least three main wave break zones with the waves reforming between each break and breaking again progressively as the water shallows up to the beach. For wave trains with Hsig generally 6 metres or less only two breaks are generated and for 3 metres or less there is usually only one significant breaking zone. Ten years observations of storms have indicated that each time a wave breaks it generates a wave set-up but that each set-up is localised to lie almost completely within the zone that the waves peak-up, break and then reform. As such for all offshore break zones each break set-up results in a local hump in the mean sea level that drains away on both sides of the breaking zone and it is only the final wave break on the beach itself that generates any set-up directly connected with the shore. The general resultant variations in mean sea level are shown diagrammatically in Fig. 7. Long term observations that the peak wave set-up within each breaking zone is approximately 25% of the breaking height seem to agree with Foster's estimates (pers. com.) but they do not support the assumption that any fixed percentage of Ho persists as a surge from the initial offshore break right onto the beach itself.

Elsewhere after great storms much evidence has been reported of apparantly unprecedented penetration by the sea to remarkable distances inland, and to such heights on dunes and local ground elevations that investigators have been led to postulate great surge levels to explain the evidence. It is quite likely however that much of this evidence has merely been the result of wave doubling. For example, eyewitness accounts record signs of wave attack levels over 13 metres above M.S.L. at Bathurst Bay in Australia in 1899 due to Cyclone "Mahina". Subsequent analyses by Silvester & Mitchell (1977) would predict a simple surge level of only 6.5 metres, but such a large cyclone must have generated many thousand waves much higher than 7 metres and it would require only one final shoaling wave of double height to reach the recorded water damage level on the shore itself, or indeed only one wave of 7 metres to ride over the beach surge, if it could penetrate that far, to attain the same result.

## 9. Revetment Wall Toe Exposure

The estimation of the likely water depth in front of a revetment wall at the time that it is likely to be exposed to a major storm is unfortunately rather a probabilistic exercise. A revetment wall is fixed in position but sandy ocean beaches are highly mobile with short term variations often completely masking long term recession or accretion, see for example Chapman and Smith (1981). The likely level of the beach in front of the wall, excluding localised toe scour will depend entirely upon where it is positioned within the overall swept prism of the beach (See Fig. 8). The swept prism represents the total mobile volume of the beach in response to all wave climates and sediment changes on the beach but the temporary response to great events, particularly in the offshore-onshore mode may be so large that long term trends are quite infinitesimal by comparison. Nevertheless some estimate of the probable limits of the swept prism must be made before the potential variations in shore level in front of the structure can be considered (See Fig. 9). Once a "hard" structure is constructed within the swept prism, that structure must be exposed to the same energy that would have been absorbed by the natural




OIAGRAM OF CROSS SECTION OF BEACH

NOTES:– VISUAL OBSERVATIONS OF BEACHES INOICATE:–

(1) EACH WAVE BREAK REFORMS ANO BREAKS AGAIN ABOUT HALF PREVIOUS "H"

(2) WAVE BREAK SETUP IS APPROX. 25% OF BREAKING WAVE HEIGHT AND IS LOCALISED WITHIN ACTUAL WAVE BREAK ZONE. WIND SETUP APPEARS CONCENTRATED MAINLY AT FINAL BEACH BREAK.

(3) GOLD COAST FINAL WAVE BREAK IS ALMOST NEVER ABOVE 3METRES SO THIRD OFFSHORE BREAK OOES NOT OCCUR UNTIL Ho EXCEEOS 7METRES.

(4) WAVE TROUGHS ARE NEARLY FLAT IN ALL WAVE BREAK ZONES BETWEEN INDIVIOUAL WAVES SO Ho SINE CURVE STRUCTURE BELOW LEVEL DATUM HAS BEEN SUPPRESSEO AT OR BEFORE FIRST OFFSHORE BREAK.

FIGURE 7- APPEARANCE OF SEA SURFACE AT GOLD COAST BEACHES DURING MAJOR CYCLONE/STORM EVENTS.

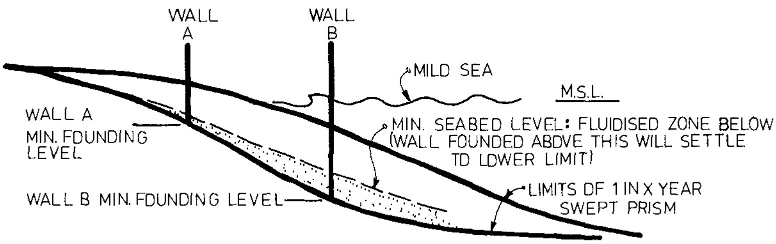



FIGURE 8:—EFFECT OF SEAWALL POSITION WITHIN SWEPT PRISM.

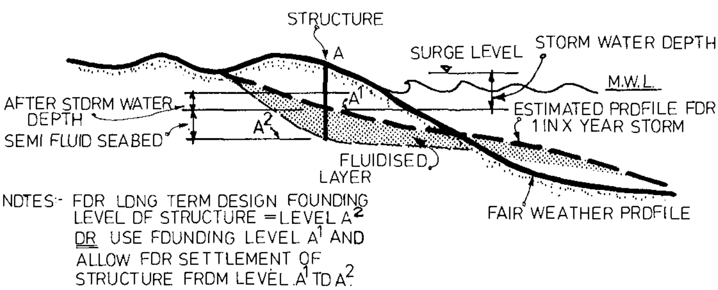



FIGURE 9:—DESIGN FOUNDING LEVELS FOR REVETMENT WALLS.

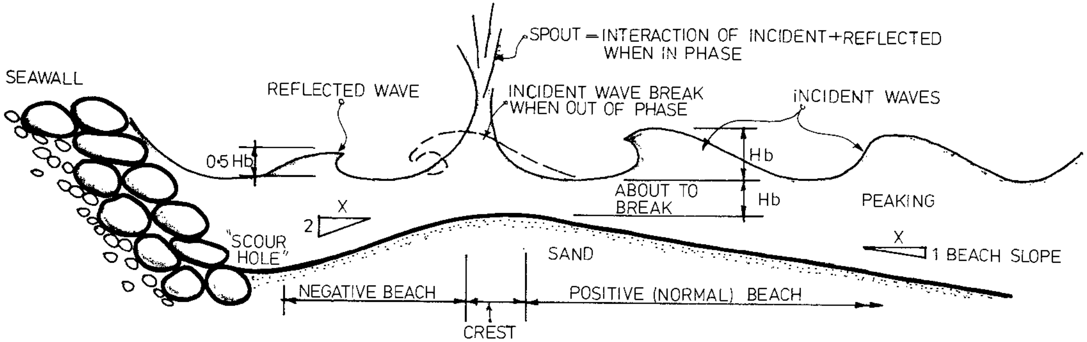
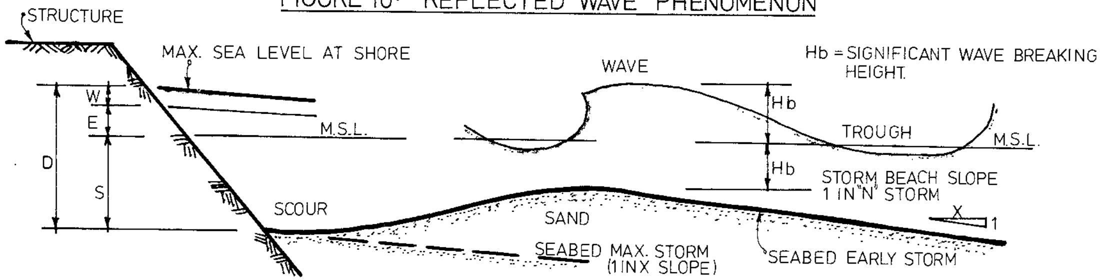



FIGURE 10:— REFLECTED WAVE PHENOMENON




D = TOTAL MAX. WATER DEPTH EXPOSURE
W = WAVE SETUP = Hb/4 (THIS FLUCTUATES)
E = CALCUATED BAROMETRIC PLUS WIND SETUP.
S = DESIGN SCOUR DEPTH = 2Hb + Hb/2 = 2·5Hb

NOTES:- MAX. POTENTIAL SINGLE WAVE ATTACKING STRUCTURE Hb(MAX.)= D.
DOUBLE WAVES WILL NOT OCCUR ONCE S > 0·75Hb AS A RULE OF THUMB.

FIGURE 11:— DESIGN HYDRAULIC EXPOSURE

beach volume now cut off from the waves by the structure itself. This it usually does in two ways - firstly by direct absorption of breaking energy by the face armour and secondly by reflecting the waves or part thereof again. Observations on the Gold Coast suggest that the reflected wave energy is then absorbed by two further concurrent processes; part of the outgoing wave energy is absorbed by the sediments themselves which adopt a "negative" beach slope in response, and the rest is absorbed by collision with the incoming waves. The total process is shown diagramatically in Fig. 10. The result is a sea-bed hollow in front of the revetment locally known as "toe scour".

Unfortunately little data have ever been collected on accurate toe scour depths but on the Gold Coast one section of boulder revetment wall during a short term beach starvation period was exposed to the ocean such that initially there was about 30 cm. of water at the toe at mean tide. Within two years the toe scour, depth "S" in Fig 11, reached 3m. at low tide and the wall had to be topped up twice, all during a calm period with the waves striking the wall seldom exceeding 1m. high. Many more observations have however been made of the magnitude of the waves reflected by boulder walls. With small waves striking rock walls reflection co-efficients of over 60% have been observed but during storms with well air entrained breaking waves (i.e. 2nd or 3rd storm breaks) the reflection co-efficient has varied between 25% and 50%. For design purposes locally the 50% factor is adopted for reasonable conservatism and the likely depths of water in front of a revetment at the beginning of a storm would be calculated as shown in Fig. 11, with depth "D" adopted for the maximum exposure at the peak of the storm.

## 10. Conclusions

On prototype revetment walls observations tend to suggest that many unexpected events occur in Nature that may seldom or never be detected in conventional flume tests on models. The most important results of local long term observations have been discussed and some of the resultant recommendations are set out below. Although the Gold Coast revetments represent only once class of such structures - that is a revetment sited with beach sediment all around it, i.e. in front, under and behind it; it is at least hoped that the "real time" observations may be of interest to some hydraulic structure designers.

## 11. Recommendations

For the design of boulder revetment walls of the simple class adopted on the Gold Coast similar to the details shown in Fig 12(a) it is recommended:-

(a) Special attention should be applied to extra toe scour delay features and additional top armour as shown in Fig. 12(b).

(b) Design wave set-up calculations should include consideration of Fig. 7.

(c) Design exposure water depths in front of revetments should include consideration of Figs. 8, 9 and 11.

(d) Wave testing of Gold Coast type revetments should be conducted in "soft bottom" tanks large enough to contain a compatible section of swept prism.

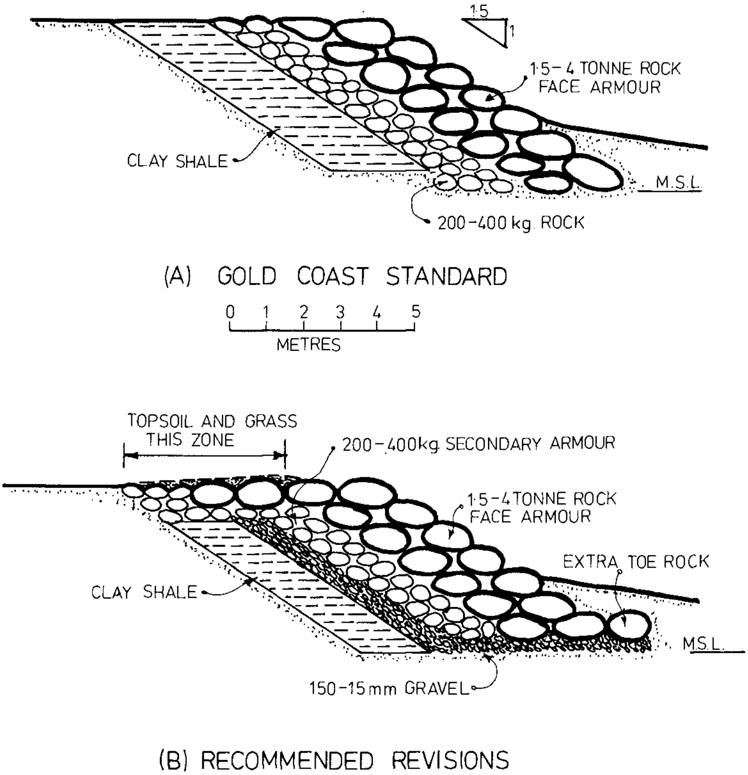



FIGURE 12:- BOULDER WALL DESIGNS

(e) There is nothing original in the concept of a "design storm" yet the basic armour and revetment stability factors might well merit the consideration of a "design event" say a cyclone or hurricane attacking the revetment for say 3 high tides of each 4 hours duration or say 3000 waves in total.

(f) Such a design wave climate might then well be simulated in the laboratory by a wave train of the form

| | | | |
|---|---|---|---|
| (i) | 1000 waves amplitude = 0.6D | period = | $10_s$ |
| (ii) | 500 waves amplitude = D | period = | $15_s$ |
| (iii) | 10 waves amplitude = 2D | period = | $20_s$ |
| (iv) | 500 waves amplitude = D | period = | $15_s$ |
| (v) | 1000 waves amplitude = 0.6 D | period = | $10_s$ |

Such a design wave climate is highly arbitary but it does hold some resemblence to what at least local prototypes must be expected to withstand during a 1 in 50 and a 1 in 100 year event.

## 12. References

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Chapman, D.M. and Smith, A.W. (1981) A Ten Year Review of Variability on an Ocean Beach. 5th Aust. Conf. on Coastal & Ocean Eng. (1981) In Press.

Silvester, R. and Mitchell, H.L. (1977) Storm Surges Around Australian Coasts. 3rd Aust. Conf. Coastal & Ocean Eng. Pub. 77/2. Inst. Eng. Aust. (1977).