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Rock ‘n’ Roll in Mound Structures

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ABSTRACT

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This note was inspired by recent years' efforts on improvements of the design and construction of mound structures for breakwaters and coastal protection. Although improved procedures have been implemented in many projects, misleading approaches still occur. Research in unit structural stability, still in its infancy, suffers from the lack of proper hydroelastic model laws that enable correct representation of the prototype in the model. Block geometries are still discussed but more sophisticated compact blocks are becoming popular as experience about their function becomes more widely appreciated and available.

ADDITIONAL INDEX WORDS: *Mound breakwaters, stability, multilegged blocks, hydroelastic models, Iribarren numbers.*

INTRODUCTION

Rock ‘n’ roll, introduced after World War II, appealed to masses of young people who found the new rhythmical forms (of dancing) at the heart of musical trends of the period. Rock ‘n’ roll, just one of the new musical forms, gradually shed its initial coarseness for more subtle rhythms and sophisticated movements.

This progressive refinement of a new trend with primitive beginnings is somewhat analogous to the development of designs of mound breakwaters. Early engineering designs based on “rude formulas” were later improved and replaced by more realistic approaches. Recent developments include the addition of structural, including “rock ‘n’ roll.” As with most contemporary music, rock ‘n’ roll is favored by “the young” who, in their enthusiasm tend to forget that a full orchestra or symphony required many different instruments, notjust the rhythmic and noisy part. At present this musical trend is in a transitional stage, rock ‘n’ rolling, with the janissary sometimes producing deafening noise so nothing else can or will be heard, if present. A symphony, however, requires coordinated and balanced instrumentation. So it is with the design and construction of mounds for breakwaters and coastal protection.

STABILITIES: CRITERIA FOR DESIGN

The three different kinds of stabilities that must be secured include (1) the overall stability, (2) the unit in place, and (3) the unit structural stability (BRUUN *et al.*, 1985). Design must be based on a number of well-defined boundary criteria that range from wave hydrodynamics, hydraulics, geomechanics, soils, materials, structural too, the most often forgotten constructional critera (BARENDS *et al.*, 1983; BRUUN, *et al.*, 1985; GÜNBAK, 1979). Some criteria are defined within rather narrow limits. Others require broader confidence and variance levels. Next comes the analyses and proper use of the data.

Wave Data

Wave data are usually considered most important. Because recorded data are almost never available in adequate quantity or quality, they must be checked by hindcastings. All hindcasting procedures are based on meteorological data, *i.e.*, winds and atmospheric pressures. They are often of low density, and consequently inadequate. Their use may lead to major uncertainties. A stringent requirement of agencies performing data collection and analysis should therefore include simultaneous evaluations of confidence levels.

The next question should focus on the forms in

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which wave data be presented for design considerations. The academic answer calls for "extreme values." The practical reply, however, deals with "an envelope covering all occurences of conditions most dangerous to stability and their corresponding frequences of occurrence." Today's "scientific practitioner" knows that it is not the "design wave" but the "wave condition(s)" that determine stability. Conditions of stability are not described by extreme wave heights and their corresponding period(s), but by certain successions of waves, wave groups, wave geometries, direction of approach, short-crestedness, depths and depth variations, and finally, but most important, by the entire interaction process of waves *vs.* structure that includes structural reactions as well (BRUUN *et al.*, 1985; GÜNBAK, 1979; JOHANNESSON and BRUUN, 1974; LOSADA and GIMÉNEZ-CURTO, 1979; SAWARAGI *et al.*, 1983). The wave criteria, therefore, is (are) neither an H_s or an H_{max} (T_s, T_{max} or T_z), occuring at low frequencies, but the properties and characteristics of all pertinent hydrodynamic parameters involved in severe storms recorded at the site, and that means where the structure will be, and not several kilometers away (BRUUN *et al.*, 1985). Following normal principles for the design of a bridge, highway or dam, one must consider all of the "live loads" associated with the time-history of the wave action, at the same time concentrating on conditions which are most dangerous to all three stabilities.

The importance of the *Iribarren number,* now usually called the *ζ-factor,* was first observed in Norway by GÜNBAK (1974), as described in BRUUN *et al.*, (1985). The resonance phenomenon was noted earlier, also in Norway (BRUUN *et al.*, 1974-1985). Its importance was soon realized in Spain (LOSADA and GIMÉNEZ-CURTO, 1979) and in Japan (SAWARAGI *et al.*, 1979). Later, the importance of wave groups was learned (BRUUN *et al.*, 1985: Canada, Denmark, Japan, Norway, Spain), and similarly for wave "jumps" and "freak waves."

As explained above, all designs should consider overall, unit-in-place, and unit structural stabilities. This does not mean that the same wave condition is equally dangerous to all three stabilities. In all cases, however, maximum wave conditions dangerous to the particular stability should be known. Such considerations not only include wave heights, but periods and joined probabilities of height and period for storm conditions of high or extreme levels. For overall and unit-in-place stability, interest should be concentrated on "resonance and beyond resonance conditions" where wave periods are equal to or in excess of uprush plus downrush periods, particularly when they occur in groups. "Jumps" and "freaks" need to be included as well. In addition, the direction of wave propagation, storm tide elevations, as they occur under extreme conditions, and the joined probability of extreme wave and tide conditions are required conditions. For the structural unit stability, not only maximum forces but also "fatigue conditions" must be considered.

It is often claimed that Weibull distributions for the prediction of H_s values of low frequency of occurence, and extreme waves by Gumbel distributions based on data recorded over at least three years, will suffice for most oceans to provide reliable data for design (BRUUN *et. al.*, 1985). This assumption, however, depends upon the quality of data recorded, and upon the method of analysis. Extrapolations from low frequencies of occurrence, for example, can never be fully correct or reliable and may lead to exaggerations as well as underestimates. The best approach is to check the results by hindcastings that include a number of extreme events that result from meteorological conditions and then use maximum values properly enveloped using confidence levels also produced by hindcastings. In this respect, the joined probabilities of height, period and tide elevations are of prime interest (BRUUN *et al.*, 1985; GÜNBAK, 1979; LOSADA and GIMÉNEZ-CURTO, 1979; SAWARAGI *et al.*, 1983). Wave research institutes should develop such information for further analysis by the designer, who must have detailed knowledge about waves *vs* structure interactions. The designer must also consider all possible future developments, *e.g.* of water depths due to sea level rise, scour or man-made changes like dredging of navigation channels which could possibly cause concentrations of wave action in local areas due to changed refractions, reflections and current activity caused by channel geometries.

Regarding the statistical aspects, one should always remember that statistical analyses are methodological tools. Analysis is never better than its database and/or method. To play safe, "the most dangerous events" must be enveloped, because they will allow evaluation of potential future damages, the damage expected from extreme events occurring at known frequencies. More important, no one will ever thank a designer for underestimating a design. Far too often laboratories have competed on a wrong philosophy in this respect.

Other Data

For a long time, it has been customary to consider waves *vs.* structure only, meaning the armor layer. Important problems, such as flows in the granular media, geomechanical conditions (*i.e.*, friction), and reaction to impacts, were generally not appreciated. These factors are better understood today, but as a profession, coastal engineers still have not come very far in researching impacts and the great importance of air in impacting waters. This is particularly important for the unit structural stability, as well as for the interior geomechanical stability (BARENDS *et al.*, 1983; BRUUN *et al.*, 1985; CIAD PROJECT GROUP, 1985). The geomechanical/hydraulic flow-model, which can be a "dry" computer model, has been introduced (CIAD PROJECT GROUP, 1985), but it does not solve the entire problem of design for hydrodynamic forces on and in the mound. In this respect, it should be noted that the maximum impact, as well as the maximum gradient flow in porous media, occur for the same ζ-values as maximum downrush and the maximum forces from wave breaking (BRUUN *et al.*, 1985; GÜNBAK, 1979; LOSADA and GIMÉNEZ-CURTO, 1979; SAWARAGI *et al.*, 1983). Materials and soils/foundation data are also important parameters. As a bridge, road or dam is designed for peak loads, dead and live, so should a mound structure. This suits a probabilistic approach (BARENDS *et al.*, 1983; BRUUN *et al.*, 1985; CIAD PROJECT GROUP, 1985). A final requirement, still in the design phase, is the incorporation of construction data, a phase sometimes ignored by designers: the contractor must also join the "design team."

Design: Overall and Unit-in-Place Stability

A number of conditions may exist which are almost equally dangerous to stability. Their probability of occurrence must be known, together with their level of damage measured in practical terms (BRUUN *et al.*, 1985). Although it has been customary to qualify damages in mound structures in terms of "sagging volumes" in the slope and "number of units left," it must be realized that the development of an S-slope and "number of units left" (*i.e.*, by rolling down), may contribute to stability of the lower slope or toe structure. The upper slope suffers damage but is relatively easy to repair. Damage, in a comprehensive view, should be described in its full perspective, not just "journalistically." This realistic approach is appreciated by practical engineers (BRUUN *et al.*, 1985; SAWARAGI *et al.*, 1983).

Damages are mostly caused by combinations of adverse factors, including hydrodynamics, hydraulics, geomechanics, soils, and materials (BARENDS *et al.*, 1983; BRUUN *et al.*, 1986; CIAD PROJECT GROUP, 1985). While the former have been fully realized, factors related to the "granular media" and its reaction to forces have not yet been accepted. Combined hydrodynamic and geomechanical data are able to predict the most dangerous conditions, the action of the forces, and the reaction of the granular media (BRUUN *et al.*, 1986; CIAD PROJECT GROUP, 1985; SAWARAGI *et al.*, 1983). Design formulas, however, constitute a departure from rational principles because they cannot possibly consider all possible adverse combinations of forces. Use of some recently proposed "improved formulas" (CIAD PROJECT GROUP, 1985), instead of rational procedures, is similar to playing a symphony with only three or four instruments, when 30 are required in order to produce a flawless performance. It is also apparent that in order to reduce the number of dangerous combinations that are adverse to stability, simplicity in design is desirable; there should also be full overlapping between force-variances and the reaction to forces by stabilizing agents and their variances. If engineers use statistical mean values for stability evaluation and, at the same time, employ "pell-mell" designs, they will still make severe mistakes in design. Is design work actually carried out "pell-mell" in other engineering fields, for structures which are supposed to carry heavy loads? No, never!

Structural Unit Stability

So far only "geometrical stabilities" (overall and unit-in-place stabilities) have been mentioned. Evaluation of these stabilities requires data of the kind described above. A new question, however, focuses on whether the same data base can be used for evaluation of the structural unit stability.

The first step in the evaluation of the unit structural stability involved recording the movements of blocks (BRUUN, *et al.*, 1985, plus references). This effort was followed by simple structural tests under idealized conditions that attempted to establish the consequences of movements recorded on film. Rocking of blocks received major attention because the process could eventually cause breaking by fatigue. Although rocking is an observable process, stresses without rocking are hard to measure, but attempts are being made to ascertain what they might be using instrumented blocks (USCE, CERC). The results of these tests, however, depend on block placement within the mound. Thousands of possibilities exist, and a lot of them may be dangerous to structural stability.

Is Rocking a Practical Criteria?

Misinterpretations have occurred when "rockings per se" were considered to be synonymous with structural unit instability rather than with instability associated with fatigue forces. It is obvious that the strongest forces result from downrush maximum velocities combined with maximum accelerations at the toe of the breaking waves, which occur almost simultaneously with impacts for the deepest downrushes or for resonance or "semi-resonance" conditions (BRUUN *et al.*, 1983). While blocks in the lower part of the slope may only rock once or twice during resonance, the situations may be very different for periods lower than resonance or when $T < T_{res}$. For these higher frequencies, rockings occur in a highly turbulent flow and therefore are more frequent, but probaby also less dangerous to the unit structural stability, because most rockings represent a lower momentum transfer. Many smaller, but less powerful, rockings could still cause breakings by fatigue.

In recent reports it was observed that diagrams gave the impression that the unit structural stability is less in higher-frequency intervals for periods lower (frequencies higher) than the resonance period. It was simply forgotten that "rocking" is more than a "movement"; it represents a momentum by its size, not just by its numbers (which limits structural stability). It should also be noted that blocks can break without any rocking, due to the momentum to which they are exposed.

Maximum of momentum by impacts are likely to occur when a plunger strikes barren slopes with no water pad, thereby causing high inertia forces approaching the shock type. Another maximum comes later, when downrush velocities reach maximum values and exert maximum drag and lift forces on the exposed blocks with possibly damaging effects to the block itself or to neighboring blocks. This happens for resonance and beyond-resonance (lower) perod(s). It is therefore hardly correct to assume that the danger range of ζ-values due to rock 'n' roll by impacts or drags are very different from those for overall and unit-in-place stabilities, that is, as far as multilegged blocks as concerned. This assumption, however, depends upon structural strength of the unit.

The most critical range of ζ for overall and unit-in-place stabilities for rock and rectangular compact blocks of concrete are indicated in the schematic (Figure 1). For structural unit stability, the diagram must be similar if substantial materials and compact geometries are considered. For multilegged blocks, diagrams are more involved. Figure 2 shows a stability diagram for overall and unit-in-place stability for multilegged blocks. With respect to structual unit-in-place stability, Figure 3 shows two different cases. For weak blocks, *i.e.*, for slim blocks or blocks composed of weak materials, all rocking is dangerous because each uprush may cause several rockings for ζ-values below resonance due to highly turbulent waters that occur when uprush and downrush meet. This situation could,

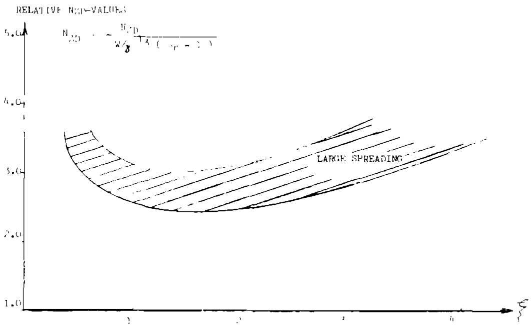

Figure 1. Relative N_{ZD} values for rock mounds: overall and unit-in-place stabilities.

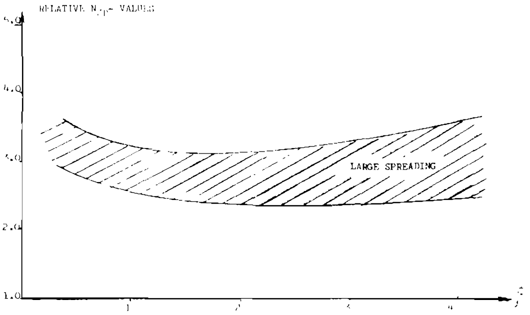

Figure 2. Relative N_{ZD} values for multilegged blocks: overall and unit-in-place stabilities.

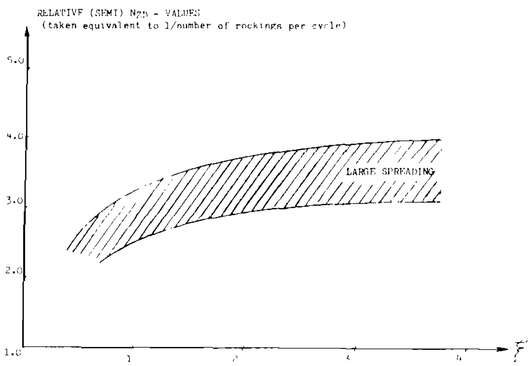

Figure 3a. Relative N_{ZD} values for slim multilegged blocks or blocks of weak materials: structural unit stability.

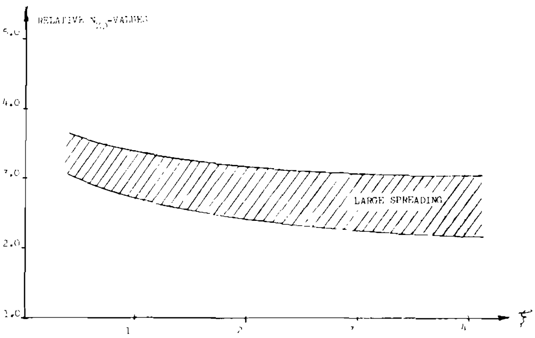

Figure 3b. Relative N_{ZD} values for sturdier multilegged blocks of stronger materials: structural unit stability.

by fatigue forces, jeopardize the structural stability of these blocks (Figure 3a). For blocks with sturdier geometries, *i.e.*, less slim or stronger materials, it is probably the major rockings (one or two per wave period) that are important because they occur for maximum impacts and/or maximum drag forces, or for resonance and beyond-resonance periods (Figure 3b). In some cases breaking takes place without rocking. With normal solid rock, *i.e.*, granites and some basalts, structural soundness is no problem. For sedimentary rock, and rock that has been exposed to strong prerssures, it could be. Stability-wise, it is critical to distinguish between the structural reaction to a great number of modest momentum and a few high-momentum rockings which could approach the zero-movement. The unit structural stability will therefore be shown as in Figure 3b. If most broken blocks in a damaged structure are found above SWL, the mechanism in Figure 3a is a likely cause. If most damage is below SWL, the mechanism in Figure 3b is the most probable cause under equal assumption of structural strength. But the blocks could, of course, also have been so weak that they were unable to carry their own weight. This sort of failure has actually happened in one situation.

The question may now be asked: "If we cannot use rocking as a criterion for instability, what shall we then use?" The obvious answer is the hydroelastic modelling as explained by Losada in BRUUN *et al.* (1985). Hydroelastic modelling is still in its infancy. It is difficult or impossible to imitate all structural stress characteristics, such as compression, tension, shear, torsion, Mohr's ratio, elasticity, and other structural properties, simultaneously and correctly in the model. Block geometry is important in this respect. Reproduction is best where stress conditions are simplified by simpler structrual configurations of the unit, and where possibilities for movement of the unit are limited. Compact and placed blocks, therefore, seem to present optimum predictable behavior, not only for overall and unit-in-place, but also for structural unit stabilities (BRUUN *et al.*, 1985).

Why Do We Accept Rock 'n' Roll Blocks?

Multilegged "brittle" blocks introduced the great interest in rock 'n' roll mound structures. Although some of the blocks broke, this was not always caused by rocking. It happened for both live and dead loads without any rocking at all. Using statistics and common sense, this observation is understandable because the number of possibilities for structurally dangerous interferences between multilegged blocks is astronomical. Consequently, some of the blocks will break. The actual number of blocks that are susceptible to breaking depends on their structural strength, including geometries and reinforcements. Unfortunate experiences with multilegged blocks during the recent decade led to improved structural designs that resulted in fewer breakings. But why not use more compact blocks instead of "brittle blocks"? The answer lies in the relatively lower quantities of concrete per unit volume of the mound. But what is gained in this way is paid for by increased risk of damages ranging from overall, unit-in-place, and structural stability. Even though the risk may be decreased by proper placement of blocks (BRUUN *et al.*, 1985), including multilegged blocks, many possibilities for breaking remain. This situation is different for mounds of regular prismatic rock or conrete blocks, where placement has proven to be a definite advantage to all three stabilities, mainly because blocks properly placed support each other and increase stability.

Revetment blocks of concrete are always regularly shaped and placed. They are laid down with a flat side on the sublayer, which in turn must provide sufficient friction against sliding. Such revetment blocks might be scaled up to breakwater blocks, as attempted by the Australian "Brown" block that has the shape of a nut. The major problem in its use implies placement on a rough sublayer that provides friction against sliding. A "mosaic" placement (like tiles in a bathroom) is contradictory to adequate friction. On the other hand, sliding forces are less for such "nut blocks" because they drain well and decrease uprush by a relatively high surface friction due to a hole in the middle. Somehow sublayer friction, porosity and placement could be joined.

Cube-blocks like the "Antifér" (BRUUN *et al.*, 1985) are very compact and drain well if placed right. They are easy to place if the sublayer is not too rough. The four grooves on the sides and the newly-invented hole in the middle contribute to draining as well as to friction towards the sublayer and sideways. It is important that the permeability is not decreased by too regular a placement. The permeability should remain at 40 to 50%. Conversely the perforation of blocks, ultimately only leaving a "frame," should not reach such levels that too little weight is left to provide friction against sliding, while at the same time too much area is left for hydrodynamic forces (from all directions) to work on. The most suitable design for a breakwater, composed of concrete units, may be found somewhere between the Antifér and the Brown, provided that the unit structural stability is secured adequately by "compactness," and temperature stresses are avoided to the extent possible. There will hardly ever be a unique answer to block geometry. The block has to be "tuned" to the local conditions of wave and materials' climate, as well as to the equipment available for construction on the local level.

Recent Attempts towards a Statistical Approach

An article by FRANCO *et al.* (1986) describes a possible approach for evaluating the probable damage of a sea structure during its usable life, on the basis of wave statistics and results from stability tests on physical models. This includes a practical example showing application of the method. The authors present a probabilistic approach to "hydraulic" as well as "rocking" damages. The statistical analyses are based on wave heights only. As admitted by the authors, groupness and wave period effects are neglected, regardless of their importance for stability (BRUUN *et al.*, 1985). The methodology can, however, be expanded to include wave groups and periods by the application of group statistics and joint probability of wave heights and periods as largely explained in BRUUN *et al.*, 1985. The character of the tests, however, would be somewhat different because they comprise an evaluation by the effects of different wave groups in resonance under extreme conditions. During the tests the behavior of the blocks should be recorded photographically, also noting water velocities. The number of rockings and movements should be observed, as should but the momentum transfer, to obtain actual forces. As mentioned earlier, breaking is not only results from "number of rockings," but of their severity; and some blocks may break without any rocking, while others may break by "fatigue-rocking." While the "hydraulic failures" (departure of blocks) are easy to observe, "rocking failures" can only be recorded properly by a tedious process requiring much experience. Field testing of course is preferable, and is now attempted by the researchers at the Coastal Engineering Center (Vicksburg, Mississippi) in actual planned breakwater tests.

A design procedure would thus include analysis of time series to ascertain the occurrence of wave groups that might be of particular danger to stability, including resonance effects under extreme conditions. By comparing the results of this kind of analysis to the results of the group testing should help evaluate the actual stability (BRUUN *et al.*, 1985). The testing will undoubtedly indicate the importance of placed blocks that increase the mutual support. These tests will also reveal the weakness of the multilegged blocks because their innumerable combinations of interference are adverse to block stability. The importance of decreasing the number of degrees of freedom will thus become obvious.

Construction

The final step in the creation of a mound structure for a port or for general coastal protection is the construction phase. Construction should never involve difficult operations that cause large variances in the quality of the product. The designer must plan on construction principles that will allow effective and precise operation. We should always remember that the contractor is the person who handles the final movements of the symphony. If the contractor fails, everything may fail, and the end result is a full-fledged rock 'n' roll performance. Construction principles are dealt with in considerable detail in BRUUN *et al.*, 1985.

CONCLUSION

Although much has been learned, there is a great deal more to learn in breakwatrer mound technology. When rock 'n' roll was introduced, it widened the musical horizon, but it also caused an oversimplification of damage criteria. Just counting the number of rockings does not produce a reliable result. It is the same as writing a ticket for a traffic speeding violation whether the speed is 5 or 100 km per hour! Speeding tickets are only given for exceeding the speed limit. In breakwater technology both are equally wrong. For the evaluation of unit structural stability, stress analyses are the key. A breakwater symphony must be played by a full orchestra.

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☐ ZUSAMMENFASSUNG ☐

Dieser Vortrag wurde von Mühen zur Verbesserungen im Bereich des Entwurfs und Konstruktion von Erdwallbauwerken für Wellenbrecher und dem Küstenschutz eingegeben. Bei vielen solcher Bauwerke gibt es verbesserte Verfahrungen zu finden, werden irreführende Verfahrungen auch noch benutzt. Die Forschung der Anlagenstabilität ist ziemlich neu und unentwickelt; da gibt es fast keine nutzbare hydroelastische Modellen, die genaue Vertretung des Urtypen ermöglicht. Die Blockgeometrie ist noch diskutiert, aber hochentwickeltere Dichtblöcke werden sehr populär, da werden ihre Möglichkeiten weitverbreitet.--*Stephen A. Murdock, CERF, Charlottesville, Virginia, USA*