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FINAL AND ANNUAL REPORT ON  
DISCONTINUED RESEARCH CONTRACT No. N00014-88-K-0690

Investigation of Parameters and Classification Relationships  
for Marine Rock Strata Quality and Anchorage Characteristics

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ABSTRACT

Contract authorization on this project was received by the principal investigator on October 17, 1988. The project was budgeted for \$197,335.00 for two years ending September 30, 1990. However, only \$15,000.00 were initially committed with further funding to be reviewed after two months from the date of authorization.

Unfortunately, no further funding could be provided due to shortage of funds and the project had to be discontinued.

Although the principal investigator had to work under very difficult conditions of project uncertainty, leading to staffing problems, research was performed in accordance with the original objectives and tasks as set out in the research proposal but compatible with the length of research time allowed by the amount of funding received.

This report provides information on the work performed up to its discontinuation. Particular progress was made concerning evaluation of index tests with reference to the Schmidt hammer test, determination of the potential of the "petite sismique" technique for ocean floor applications, and consideration of possible approaches for assessing the rock mass strength of sea floors.

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## INTRODUCTION

Two semi-annual progress reports were submitted on this project to the Administrative Officer of the contract (Mr. Norman A. Meeks) with copies provided to the Scientific Officer (Mr. Andrew DelCollo). The reports were dated April 17, 1989 and October 30, 1989.

With the award of this contract, the amount budgeted for this project was \$197,335.00 for two years, however, only \$15,000.00 or 7.6% of the total estimated cost was received. Further funding proved to be uncertain which prevented an appointment of a graduate student on this project since this would require a minimum commitment of one academic year or at least a semester. Moreover, any prospective student would expect a research topic to continue for the duration of a graduate degree which, in the case of an M.S. degree, is of more than one year's duration at Penn State.

When it became apparent that due to the shortage of funds the contract could not be continued, the principal investigator - in the absence of a graduate assistant- was obligated to carry out the research himself within the limits of the available funds. These funds (\$15,000), after subtracting the amounts due to for fringe benefits and indirect costs as well as the direct costs for equipment purchase (two portable Schmidt hammers), provided for only about 4 weeks of the principal investigator's time.

## RESEARCH TASKS SPECIFIED IN THE ORIGINAL PROPOSAL

The proposed two-year research program envisaged investigating parameters and determining classification relationships that could incorporate rapidly and remotely determined geologic and geophysical parameters relevant to the overall quality and anchorage characteristics of seafloor rock strata.

The approach used in the proposed research afford was fivefold:

- (i) to assess index tests for rapid and remote estimates of the strength and/or hardness of marine rocks as input data for a modified rock mass rating system;
- (ii) to perform appropriate laboratory tests on marine rocks to characterize the rock

- materials at typical sites where anchorage holding capacity needed to be assessed;
- (iii) to analyze a special geophysical technique, such as the "petite sismique" method, for assessing its potential for determining seafloor rock structure conditions;
- (iv) to evolve calculation procedures along the line of the Rock Mass Rating (RMR) classification system (modified for seafloors) for relating rock strata quality to anchorage holding characteristics;
- (v) to assess the validity of these procedures through field trials and case histories back-analyses.

The specific scientific tasks and their justification are given below. In essence, it was envisioned in the research proposal that an effective rock classification approach for seafloor applications will be based on two main classification parameter types: rock material strength and rock mass structure characteristics, e.g. blockiness. Appropriate numerical values for each type of parameters would be related to the overall seafloor conditions for engineering purposes, and to the anchorage holding capacity. The research tasks identified contribute directly to this overall purpose.

Task 1: Material strength/hardness. This task provides the necessary input information for the material strength parameter but it also aims to do it in a fashion appropriate for naval operations: quickly, remotely, and reliably. For this purpose an index test should be selected, i.e. a test which indirectly estimates the needed property without the necessity for direct laboratory tests. There are many index tests to choose from but, for this application, the Schmidt Hammer strength index test seems most promising and should be studied in detail. It is a rebound-type test indirectly related to the uniaxial compressive strength of rock material.

Task 2: Data for typical sites. This task is urgently needed because virtually nothing is known about the mechanical properties of seafloor rocks at the typical naval sites. Although the projectile embedded anchors have already been field tested, the test sites were not properly characterized during the trials since only very limited borings have been performed. If an appropriate apparatus is to be developed under Task 1, the rock types to be expected and the range of their mechanical and physical properties must be known.

Task 3: Rock mass structure. This task is to provide the necessary input information for the second classification parameter: rock mass structure or blockiness. Although standard geophysical techniques immediately come to mind, e.g. seismic velocity surveys, alternative methods are also needed to cross-check the results. This is particularly important in the case of this second classification parameter which is more important than the first one (rock material strength) and is more difficult to determine reliably. It is proposed to investigate a novel method known as the "petite sismique" technique. Developed in France, the technique relates the frequency of shear waves to the static modulus of deformation and to the structural quality of the rock mass. It has been used extensively in the design of the foundations for large dams but never for marine applications. The principal investigator has previous experience with this method, both in tunneling and in mining applications, and already has all the equipment needed for this purpose at Penn State.

Task 4. Anchorage characteristics relationships. This task is needed to relate or "translate" the determined rock mass quality into anchorage holding capacity. After all, the projectile embedded anchors may not function properly if the seafloor holding capacity is such that anchors either cannot penetrate sufficiently or may pull out too easily after embedment. The relationship between rock mass rating and anchorage capacity needs to be substantiated and such an empirical approach will complement well the research in progress at MIT and the Lawrence Berkeley Laboratory concerning anchorage holding relationships. The principal investigator, who developed one of the two most commonly used rock mass classification systems - the RMR system and who recently published a book entitled "Engineering Rock Mass Classifications" (John Wiley & Sons, 1989), proposed to develop an empirical rock quality RMR vs anchorage relationship for which the Hoek-Brown rock mass strength concept (which utilizes the RMR system) would serve as a starting point.

Task 5: Validity of the classification approach. This task is necessary to validate the whole research effort and would involve actually performing a full scale trial at sea featuring projectile embedment operations.

## RESEARCH PERFORMED

In view of less than four weeks of the principal investigator's time being funded for this project, only a limited amount of work could be performed on Tasks 1, 3 and 4 while no work could be done on Tasks 2 and 5 (no rock specimens were received for testing and no sea trials were undertaken).

### Summary of Work accomplished under Task 1 : Estimation of material strength using the Schmidt hammer strength index

Strength index tests play an important role in practical rock engineering (Bieniawski, 1974, 1975; Poole and Farmer, 1980; O'Rourke, 1989). They are convenient and economical tools but they also have their limitations which need to be recognized for an individual application. For estimating the strength of rock materials, the point-load test (Bieniawski, 1975) and the Schmidt hammer rebound test (ISRM, 1980) are the best known.

A detailed review of the relevant literature was performed during this study (see References) and it was concluded that the Schmidt hammer rebound test would be most suitable for estimating the material strength of the submerged seafloor strata. The principal investigator found the Schmidt hammer an easy device to use and one that can provide consistent results (Pool and Farmer, 1980) provided that care is exercised in the correct use of the instrument (ISRM, 1980) and in the interpretation of the results. Moreover, this instrument has already been considered by the Naval Civil Engineering Laboratory as a rock classifier (Johnson, 1986). The purpose of this section is to point out the potential and the limitations of this type of an instrument and to suggest some future studies.

The Schmidt hammer employs an impact plunger that is depressed against the tested surface causing compression of a spring in the hammer. After reaching a specified level of energy in the spring, it is automatically released pushing a sliding hammer mass which strikes against the impact plunger. The height of the rebound of the hammer mass after impact on the test surface (read off the calibrated scale) is a measure of the hardness of

the material. This in turn can be correlated with the uniaxial compressive strength of the rock material.

As pointed out by O'Rourke (1989), a good correlation ( $r = 0.88$ ) was found between the uniaxial compressive strength and the Schmidt hardness number. Figure 1 shows results from a study of rock samples from the Paradox Basin of eastern Utah which showed a fair correlation.

Recently, Sheorey et al (1984) obtained some 2000 Schmidt hammer results from 20 coal seams where the instrument was used in situ. They compared these data with the uniaxial compressive strength of three to six 1 ft (0.3 m) cubes tested from each coal seam. They found that the lower mean (mean of rebound values less the arithmetic mean) provided this linear relation ( $r = 0.938$ ):

$$S = 0.4 R_{LM} - 3.6$$

The above equation was recommended for estimating the (conservative) in situ crushing strength of coal,  $S$  in MPa, of 1 ft (0.3 m) cubes from the Schmidt hammer (type N) rebound value  $R_{LM}$ .

It is believed that the work by Sheorey et al (1984) is very significant and offers much promise for seafloor applications because of its relevance to the strength of rock strata composed of geological discontinuities.

The NCEL has already developed a Schmidt hammer version for underwater use (Johnson, 1986) but the rock classifier (as it is known) requires much more work concerning data analysis. At present, the instrument draft manual contains information for estimating the compressive strength and tangent modulus of a rock material based on the 1966 Deere-Miller classification (Deere and Miller, 1966).

It is recommended that a detailed study be undertaken leading to a relationship between the Schmidt hammer data from submerged rock formations and the uniaxial compressive strength of dry and saturated rock specimens from the sites where the propellant embedded anchors were tested and from the sites where future tests are contemplated. The presently used data analysis for the rock classifier is simply invalid because the Deere-Miller classification of 1966 applies to dry rock only.

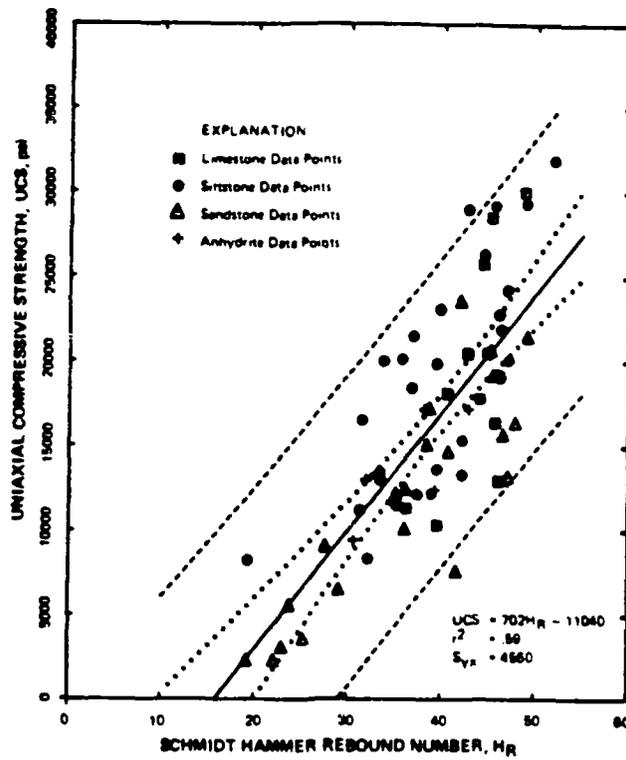


FIGURE 1 Correlation between the Schmidt hammer hardness and the uniaxial compressive strength (after O'Rourke, 1989).

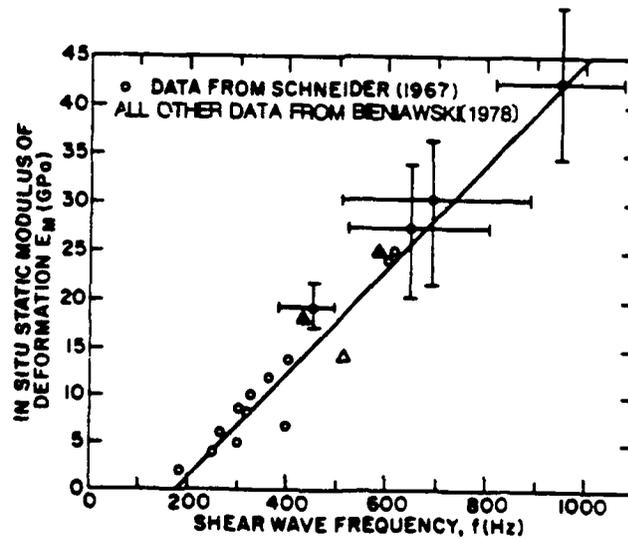


FIGURE 2 Correlation between static modulus of deformation from plate bearing tests and shear-wave frequency from 'petite sismique' (after Bieniawski, 1980).

**Summary of Work Accomplished Under Task 3: Estimating rock mass structure (blockines).**

While many geophysical techniques may be employed to assess a rock mass structure and the effect of the geological discontinuities, a novel but little-used method exists which is particularly useful for civil engineering applications. Developed in France and named the "petite sismique" technique (Bieniawski, 1980) the method is hardly known in the United States in spite of its potential. Apart from the research by the principal investigator some time ago, the only other researcher involved in the USA was Heuze (1981).

The purpose of this study was to review the "petite sismique" technique and its principles and to assess its potential for seafloor applications.

The "petite sismique" technique utilizes a seismic refraction survey emphasizing a correlation between shear-wave frequency and the static deformation modulus. Although the technique was introduced in 1967, it has not been used extensively due to difficulties in shear-wave generation and detection. Recent developments in geophysical instrumentation should provide better opportunities for wider applications of this method. In this respect, a reliable shear-wave should be of prime consideration. The benefits could be considerable: unlike many geophysical techniques that focus on wave-velocity determinations and culminate in seismic values of rock properties or identification of rock transition zones, petite sismique emphasizes static rock property evaluation from shear wave frequency data because shear waves are better indicators of rock quality than longitudinal waves.

Correlation of the shear-wave frequencies with the static modulus of deformation obtained from plate-bearing tests resulted in the empirical relationship shown in Figure 2. The principal investigator has found that a signal enhancement seismograph and directional geophones are essential to obtain good shear-wave arrivals. Moreover, an improved shear-wave generating source and data-recording procedures together with detailed engineering geological mapping of the test sites should be considered for any field trials aimed to verify the existing correlations.

The Lawrence Livermore National Laboratory conducted a series of rock mechanics field tests at the Nevada Test Site (Heuze, 1981). This included the petite sismique technique the results of which agreed with the correlation depicted in Figure 2. However,

upon inspection of the physical record, the waveform is typical of a resonant waveform.

Another study, by Belesky et al (1984), involved petite sismique tests on coal pillars and it did not confirm the data trend in Figure 2. The discrepancy was attributed to differences in characteristics of the shear-wave sources used in the investigations compared. On the other hand, Krzyszton (1984) provided theoretical justification for the empirical relationship between the static modulus of deformation and the shear wave frequencies.

The principal investigator has determined that the petite sismique technique would be a feasible means for assessing the rock mass structure of seafloor rock strata. However, much work is required before a full potential of this method is realized. In particular, the following recommendations are made:

- 1) A reproducible standardized shear-wave source is essential and for this purpose the Schmidt hammer should be tried. Such work would fit in well with the studies under Task 1.
- 2) Flat-response, hi-fidelity geophones are needed to eliminate mechanical resonances.
- 3) *Magnetic recording and high recording speeds are needed to analyze the frequency results.*
- 4) A detailed laboratory investigation is called for, which would be directed at optimizing geophone mount, source type, blow orientation and geophone type in addition to selecting optimal record gain and filtering.
- 5) The petite sismique approach for seafloor applications need not necessarily aim at determination of the actual modulus of deformation but to establish an "identification profile" of a rock mass featuring shear wave velocity and attenuation 'envelopes,' the latter being the reciprocal slope of the graph showing an increase of seismograph gain control setting with distance.

#### **Summary of Work Accomplished Under Task 4: Estimating the Strength of Seafloor Strata for Anchorage Holding Capacity.**

It has been shown (Bieniawski, 1987) that the Rock Mass Rating classification system can be modified to assess the quality of rock strata in seafloors. While much work remains to be done to finalize the structure and the parameter ratings for the

modified RMR system, no major difficulties are envisaged in this respect (Bieniawski, 1989). What is particularly challenging, however, is development of an empirical relationship between the modified RMR and the anchorage holding capacity. Such a development would be very valuable as it would complement the research already in progress at MIT and at the Lawrence Berkeley Laboratory concerning anchorage holding relationships.

The first phase of such a development work was initiated during the present study. This involved consideration of the Hoek-Brown rock mass strength concept (1986) which utilizes the RMR system. Other approaches were also examined. It was found that there are two promising approaches for estimating the rock mass strength (which in turn could be related to anchorage holding capacity as is done in the design of rock foundations). One such an approach is based on the Hoek-Brown criterion while the other is based on the Yudhbir-Bieniawski criterion. Both approaches are briefly explained below.

The empirical criterion proposed by Hoek and Brown (1980) enables estimation of the strength of rock masses using the expression :

$$\sigma_1 = \sigma_3 + \sqrt{m \sigma_3 \sigma_c + s \sigma_c^2}$$

where  $\sigma_1$  = major principal stress at failure

$\sigma_3$  = applied minor principal stress

$\sigma_c$  = uniaxial compressive strength of the rock material

$m$  and  $s$  are constants depending on the properties of the rock and the extent to which it was fractured by being subjected to  $\sigma_1$  and  $\sigma_3$ .

For intact rock material,  $m = m_i$  is determined from a fit of the above equation to triaxial test data from laboratory specimens, taking  $s=1$ . For rock masses, use is made of the rock mass rating RMR as suggested by Hoek and Brown (1988):

When rock mass is undisturbed (e.g. carefully blasted or machine excavated rock) :

$$m = m_i \exp [ (RMR-100) / 28 ]$$

$$s = \exp [ (RMR-100) / 9 ]$$

When rock mass is disturbed (as in slopes or blast-damaged rock) :

$$m = m_i \exp [ (RMR-100) / 14 ]$$

$$s = \exp [ (RMR-100) / 6 ]$$

where RMR is the basic (unadjusted) rock mass rating from the Geomechanics Classification (Bieniawski, 1979).

More recently Yudhbir (1983) suggested a rock mass criterion of the form proposed by Bieniawski (1974), namely :

$$\frac{\sigma_1}{\sigma_c} = A + B \cdot \left[ \frac{\sigma_1}{\sigma_c} \right]^a$$

where  $a=0.75$  and  $A$  is a function of rock mass quality (note that  $A = 1$  for intact rock), namely

$$A = \exp (0.0765 \text{ RMR} - 7.65)$$

and  $B$  depends on rock type as determined by Bieniawski (1974) for these rock types :

shale and limestone	B=2.0
siltstone and mudstone	B=3.0
quartzite, sandstone, dolerite	B=4.5
very hard quartzite	B=4.5
norite, and granite	B=5.0

It is recommended that the empirical approach for estimating the anchorage holding capacity, via a rock mass strength estimate based on rock mass classification, should be pursued vigorously as it holds much promise as a supplement to the analytical research conducted by MIT and LBNL. At the time of writing, more of this type of research on rock mass strength is apparently already undertaken in India by Ramamurthy (personal communication). Unfortunately, with the abrupt discontinuation of this research project much valuable momentum and initiative has been lost.

## CONCLUSION

The funding provided for the research described in this report constituted only 7.6% of the originally budgeted amount of \$197,335.00 for two years. Unfortunately, no further funding was made available and the project had to be discontinued. Accordingly, the original objectives of the project could not have been fulfilled. In spite of the considerable uncertainty and anxiety under which the principal investigator had to labor, good progress was maintained on those research tasks which could be undertaken and what was possible within the amount of the time funded. In essence, the research performed amounted to literature research since neither time nor rock samples were available for laboratory testing.

In particular, promising findings have emerged concerning the Schmidt hammer index test and the "petite sismique" technique. Most significant, however, was the work reported on empirical determinations of rock mass quality by 'petite sismique and on determination of the rock strata strength in seafloors. An approach was outlined which is considered to be invaluable to the projectile embedment project by the Navy. It is recommended that this would warrant a separate investigation of that topic.

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