Stress Corrosion Cracking and Delayed Increase in Penetration Resistance after Dynamic Compaction of Sand

R.L. Michalowski[1], F. ASCE and S. S. Nadukuru[2], Student Member, ASCE

[1]University of Michigan, Department of Civil and Environmental Engineering, Ann Arbor, MI 48109-2125, U.S.A.; rlmich@umich.edu, tel: 734 763-2146, fax: 734 764-4292
[2] University of Michigan, Department of Civil and Environmental Engineering, Ann Arbor, MI 48109-2125, U.S.A.; siddu@umich.edu

ABSTRACT

Dynamically compacted sands exhibit a drop in cone penetration resistance immediately after compaction, but a gradual increase in the resistance occurs in a matter of weeks and months. An explanation of this phenomenon is suggested, based on the process of *stress corrosion cracking* of the micro-morphological features on the surface of the sand grains at the contacts. This process, also referred to as *static fatigue*, leads to a change in the macroscopic elastic moduli of the sand, which, in turn, causes an increase in the macroscopic horizontal stress under one-dimensional strain conditions. Consequently, delayed increase in the horizontal stress leads to the time-dependent increase in the penetration resistance of the sand bed.

INTRODUCTION

Compaction of saturated sands by dynamic means (blasting, vibro-compaction) leads to liquefaction of the medium, followed by settlement indicating an increase in density of the sand bed. Surprisingly, cone penetration tests immediately after compaction indicate a drop in the penetration resistance when compared to the pre-compacted state. The penetration resistance does increase, however, in the weeks and months after the compaction process. Attention to this phenomenon was brought early by Mitchell and Solymar (1984), Schmertmann (1987), and others, but the phenomenon is still referred to as a continuing *Enigma* (Mitchell 2008).

Early attempts to explain this phenomenon focused on possible mineral dissolution and bonding between grains. This bonding would be destroyed in the process of liquefaction caused by dynamic compaction, but be re-built in time after compaction. Dissolution of minerals and pressure solution are phenomena that play an important role in the formation of sedimentary rocks, but the evidence of these processes being important in sand at the engineering temporal scale is not available, beyond experiments with halite (rock salt) that is particularly susceptible to dissolution (Tada and Siever 1985, Hickman and Evans 1995). Current efforts toward the explanation of the peculiar behavior of sands after dynamic compaction shifted the emphasis on the processes of rearrangement of particles that is part of what is often referred to as the *secondary compression* process. This rearrangement, however, cannot occur without a cause, and this article focuses on a phenomenon that is likely to be a source of the time-dependent process observed in sand beds after dynamic compaction.

PREVIOUS STUDIES

This Section is not intended as a survey of the pertinent literature, and only several sources are cited that are directly used in support of the hypothesis presented. A convincing evidence for the time-dependent increase in penetration resistance after dynamic compaction was presented by Mitchell and Solymar (1984), and an example of the cone penetration resistance before and after compaction is illustrated in Fig. 1.

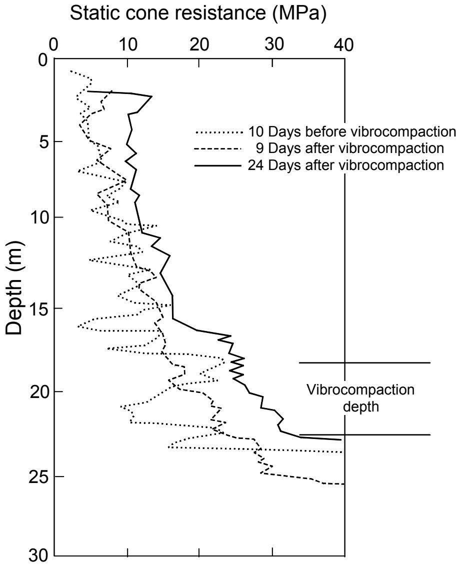

Figure 1. Variation in cone penetration resistance after dynamic compaction (redrawn from Mitchell and Solymar, 1984).

While the early attempts at explanation of the phenomenon included mineral dissolution and bond formation between grains, Schmertmann (1987, 1991) and Mesri *et al.* (1990) indicated that the changing stress state in the soil bed may be an important factor in the process of time-delayed increase in penetration resistance.

Increase in penetration resistance was detected on the laboratory scale by Dowding and Hryciw (1986), who worked with saturated sand in a drum of 107 cm in diameter. Not only the increase in the resistance to a scaled-down penetrometer was detected after dynamic compaction, but an increase was found, though to a much lesser extent, in sand that was placed in the drum, but not subjected to dynamic compaction.

Two other important pieces of information come from the paper of Afifi and Woods (1971) who presented evidence that the speed of propagation of shear waves increases in time in sand subjected to sustained stress. These results indicate that the macroscopic elastic properties of sand change in time under sustained loads. The second important observation of Afifi and Woods (1971) was in detecting a larger time-delayed increase in the wave velocity in sand with finer grains.

The last piece of information important to the hypothesis presented in this article is in triaxial test results of Daramola (1980), on sand specimens subjected to different periods of sustained load prior to triaxial compression. Specimens of Ham River sand were subjected to a confining pressure of 400 kPa for 10, 30, and 152 days prior to testing. One specimen was tested immediately after confining pressure was applied. The stress-strain curves from this testing are shown in Fig. 2. The stiffness of the sand was affected significantly by the length of time the specimens were subjected to loading prior to testing, but the strength of the sand does not seem to be very sensitive to that time.

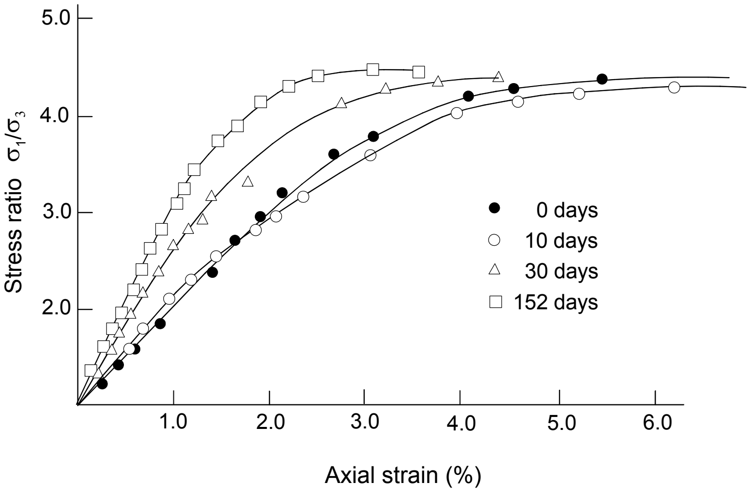

Figure 2. Stress-strain behavior of Ham River sand subjected to different periods of sustained confining pressure prior to triaxial compression (redrawn from Daramola, 1980).

A more comprehensive literature of the subject can be found in Mitchell (2008) and Baxter and Mitchell (2004).

MORPHOLOGY OF GRAIN SURFACES AND STATIC FATIGUE

Engineering behavior of soils is measured at the macroscopic scale, but this behavior is affected by the processes across the spatial scales. For the purpose of this study three scales are distinguished: *microscopic* scale, *meso*, and *macro* scale. The microscopic scale relates to a single contact and its morphology, the meso scale pertains to the assemblies of grains with their packing topology (fabric), and the macro scale includes the description of the behavior in terms of averaged stresses and strains (or strain-rates). The macroscopic description of soil behavior is indispensible in solving engineering problems, but the explanation of the cause of that behavior must be sought at the scale of grains and contacts.

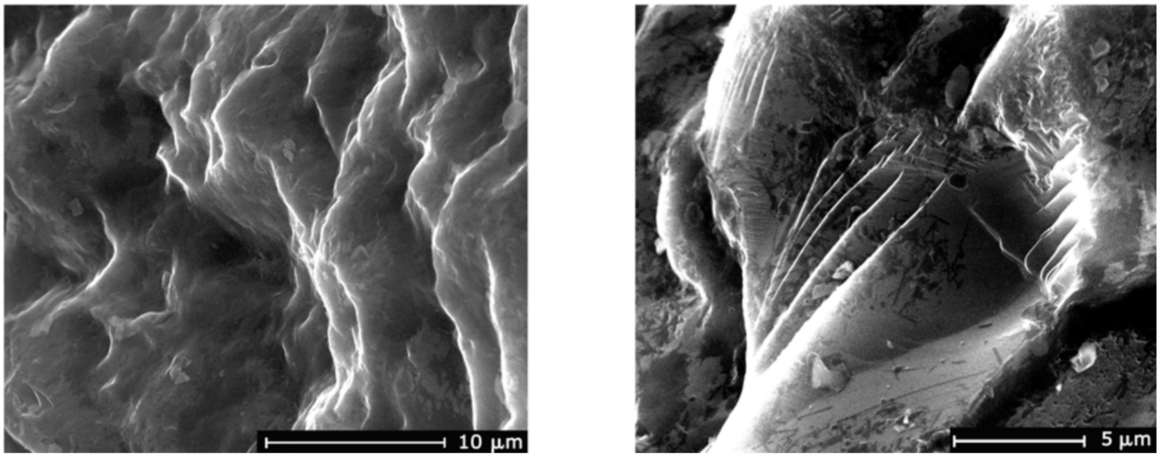

Figure 3. Morphology of sand grain surface: Ottawa 20-30 sand.

Morphology of the grain surfaces of Ottawa sand is shown in Fig. 3. Behavior of granular materials is often simulated using the discrete element method. Sand grains are typically approximated with shapes that can be handled by numerical algorithms (spheres, ellipsoids, quadrics), and the contacts are idealized by some, typically linear, force-displacement law with a limit set usually by friction. While such an approach can be quite useful, the complexity of interaction of grains with surfaces as those in Fig. 3 brings a wealth of possible responses to loading that cannot be captured with a simple linear force-displacement law.

STRESS CORROSION CRACKING OR STATIC FATIGUE

When two grains come into contact, the micro-morphologic features, as those in Fig. 3, undergo compression, shear and bending causing fracture in microscopic asperities and crystalline debris fragments. This fracturing, however, does not occur immediately after the contact is loaded; rather, it is a time-delayed process, and this micro-fracturing does not occur simultaneously at all contacts. This process is referred to here as *static fatigue*, but, as opposed to the earlier uses of this term, it pertains here only to the microscopic morphological features at the grain contacts.

Time-delayed micro-fracturing, or static fatigue, of rocks was identified earlier as a possible source of creep in brittle rocks (Scholz 1968), and has been known since the 1950s to affect rate-dependent behavior of materials, such as quartz (Charles 1958). Static fatigue is also known as *stress corrosion cracking*, as the process is dependent on the presence of moisture. For instance, the stress due to bending of fiber optic cables leads to static fatigue, and the process is affected by the presence of moisture (Cuallar et al. 1987). More recently, Lade and Karimpour (2010) indicated static fatigue as the source of rate effects in sand. They focused on time-delayed cracking of entire grains as the origin of creep in sand.

A hypothesis is presented in this paper to explain the initial drop and the subsequent gradual increase in cone penetration resistance in dynamically compacted sands. This hypothesis hinges on stress corrosion cracking of the micro-morphological features at contacts between grains. This micro-cracking causes the grains to move closer together by a distance comparable with a fraction of the size of the asperities on the grain surface (order of microns). This *grain convergence* leads to firmer contacts, thus an increase in the contact stiffness that will propagate through the spatial scales to be manifested at the macroscopic scale as an increase in macroscopic shear modulus (elastic property). This process is time-delayed, as stress corrosion cracking does not occur at all contacts simultaneously. Evidence supporting this hypothesis is in measurements of the shear wave velocity in specimens of sand subjected to sustained load. Afifi and Woods (1971) reported that the speed of the elastic waves increase in time. In air-dry Ottawa sand, the shear modulus was found to increase about 2% to 5% per log cycle of time. They also noted that the relative increase in shear modulus was larger with the decrease in the particle size. In specimens of the same size, the number of contacts increases with the decrease in the grain size. Therefore, one would expect the macroscopic effect of the process that occurs at inter-granular contacts to be more distinct in finer materials.

The fundamental conclusion from the measurements of the speed of the shear wave propagation indicates that the elastic moduli of sand increase in time if the sand is subjected to persistent load. We refer to elastic moduli rather than one elastic modulus, as the sand deposited under gravity conditions is typically cross-anisotropic, and characterized by at least two moduli and three Poisson's ratios. The authors propose the hypothesis that it is stress corrosion cracking of the microscopic features at the contacts between grains that is a direct cause of *grain convergence* and the increase in elastic moduli of sand.

CONSEQUENCES OF DYNAMIC DISTURBANCE OF SAND

Sand compaction requires a change in its fabric, so that the volume of pores can be reduced. Therefore, in the course of the compaction process some inter-granular contacts will undergo shearing/sliding, some will be lost, and many new contacts will be formed. The process of static fatigue (or stress corrosion cracking) will then start at new contacts, leading to grain convergence and an increase in macroscopic elastic moduli of sand.

Consider the dynamic compaction of saturated sand. Blasting or vibrations will cause liquefaction of the sand, the contacts between grains will be momentarily lost, and both vertical and horizontal effective stresses will become zero while the soil is liquefied. Upon dissipation of the excess pore water pressure, new contacts will be formed. During the development of the denser fabric, the contact forces will be induced (force chains) such that the macroscopic vertical stresses will be in equilibrium with gravity forces, but the horizontal stress does not have a comparable governing rule. The horizontal stress need only be such so that the deviatoric stress does not exceed the strength of the newly compacted sand. It is postulated that this stress is lower than that before compaction.

To support this postulate we illustrate the after-liquefaction development of the effective stress state in a granular assembly using the discrete element method (PFC3D). We omit the details of the simulation and only present the key findings. Of the total number of particles in a cubical specimen (approx. 12,000), 25% have elongated shape constructed of two overlapped and bonded spherical grains ("clumps"), the remaining particles are all spherical. The "clumps" are marked darker in Fig. 4(a). The fluid in pore space is not modeled; rather, liquefaction is simulated by a small reduction in the size of all grains (0.7% reduction in grain diameters), causing a sudden loss of all contacts (without producing a meaningful reduction in the void ratio). Upon re-gaining the firm contacts between the particles, macroscopic vertical stress has reached its linear distribution governed by gravity as before "liquefaction," but the horizontal stress rose to a magnitude lower than that before loss of contacts. The average ratio of the macroscopic horizontal-to-vertical stress was 0.468 before "liquefaction" and it dropped to 0.355 after re-gaining the contacts. This ratio was calculated as the average $\bar{\sigma}_x$ and $\bar{\sigma}_y$ stresses to the average of $\bar{\sigma}_z$ (Fig. 4(a)), and it is consistent with the definition of K_0. This simulation supports the hypothesis of the reduced horizontal stress caused by dynamic compaction, even though it is only a numerical evidence. This reduction in horizontal stress causes an increase in deviatoric stress, moving the stress state closer to the state of yielding.

The average stress state in the specimen before and after liquefaction is illustrated in Fig. 4(b). The yield condition in Fig. 4(b) was determined by subjecting the specimen (numerically) to triaxial compression.

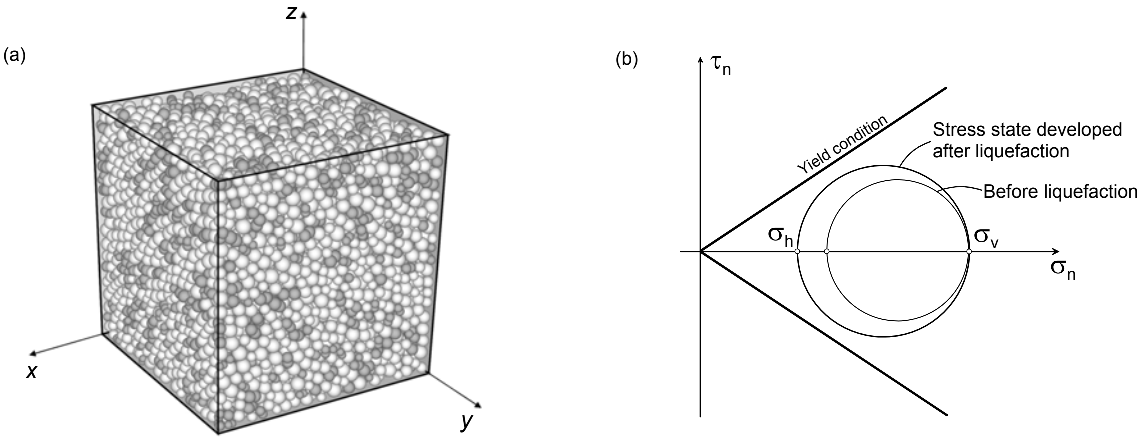

Figure 4. (a) Discrete element model of granular assembly, and (b) stress state before and after liquefaction (DEM simulation using *PFC*^{3D} code).

Once the inter-granular contacts are re-gained, the process of stress corrosion cracking is initiated. The strength of the sand increases immediately after it is compacted, but, surprisingly, the cone penetration resistance often appears to drop compared to that before compaction. The cone penetration test (CPT) is not a test in which the soil strength is measured directly. Interpretation of the test in terms of the soil strength requires a solution to an inverse problem, and this solution is dependent not just on the soil strength, but also on the existing stress state in the soil tested. It is argued here that the dynamic compaction process, while it increased the strength of the soil immediately, it also altered the stress state in the sand bed, as illustrated in Fig. 4(b), causing an adverse effect measured by the penetration cone.

Time delayed increase in penetration resistance is then caused by the increase in the horizontal stress in the sand bed due to an increase in elastic moduli of the sand produced by the process of stress corrosion cracking and subsequent grain convergence.

Evidence supporting this interpretation of the compaction effect and time-delayed increase of resistance in CPT is in the triaxial test results of Daramola (1980) who indicated that the sustained load on sand did not produce an increase in the strength, but it did result in the increase in stiffness, Fig. 2. This is because the strength is governed predominantly by the meso-scale characteristics, *i.e.*, the soil specific volume (or void ratio) and fabric, and these characteristics are altered during compaction, but they are not changed during the following period of rest under sustained (gravity) load. The time-delayed fracturing, however, leads to grain convergence and a change in macroscopic elastic properties. It is argued here that the delayed increase in elastic moduli leads, under one-dimensional strain conditions, to the increase in horizontal stress in the sand bed, which, in turn, produces time-delayed increase in cone penetration resistance after dynamic compaction.

To demonstrate this change in the stress state, consider a spring between two unyielding supports, Fig. 5(a). The force in the spring is analogous to the horizontal stress in the soil. Now, consider a time-dependent increase in the spring constant from its initial value K_1 to K_2, analogous to an increase in the macroscopic elastic modulus of the sand. This will cause an increase in the spring force, as the spring supports are not yielding (analogous to one-dimensional strain conditions), and this is illustrated in Fig. 5(b).

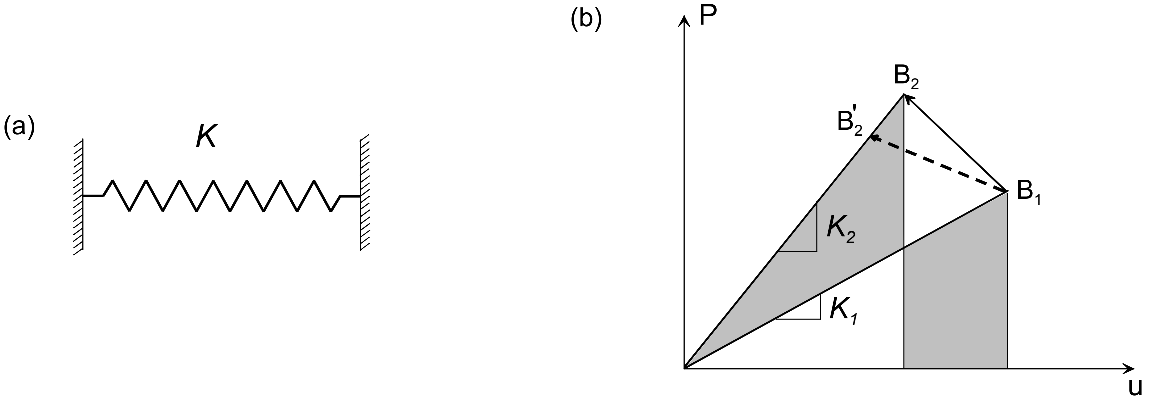

Figure 5. (a) Spring analog, and (b) strain energy.

Once the spring constant increases from K_1 to K_2, the force in the spring changes from B_1 to B_2, preserving the elastic energy (the shaded areas are equal to one another). Should the change in material property K require expenditure of energy, the force in the spring may still increase, though to some lower level at B'_2.

The increase in the horizontal stress in the sand bed after dynamic compaction is analogous to the increase in the spring force in Fig. 5. This process is delayed, because the stress corrosion cracking (the origin of the process) is a function of time. The vertical stress in the sand bed, however, remains unchanged, since it is governed by gravity. Consequently, the increase in the horizontal stress in the sand bed produces a reduction in the deviatoric stress, and moves the stress state further away from the yield condition. This is illustrated in Fig. 6 with a reduction in the diameter of the stress circle as the minor principal stress increases.

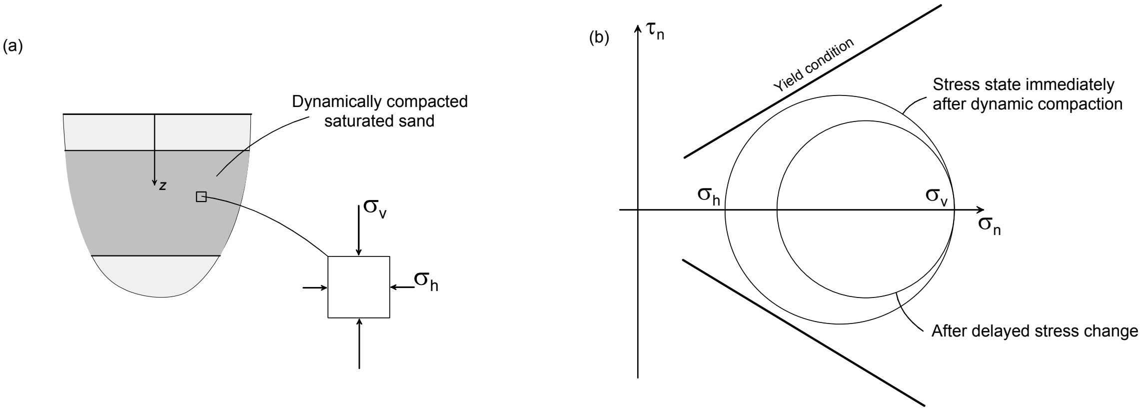

Figure 6. (a) Sand bed in 1D strain state, (b) time-delayed reduction (relaxation) in deviatoric stress.

The drop in the cone penetration resistance immediately after dynamic compaction is the result of superimposing the load over the soil that is already in the stress state close to yielding. Static fatigue at inter-granular contacts and gradual increase in elastic moduli lead then to time-delayed increase in the horizontal stress and moving the stress state further away from its yielding state. Consequently, the cone penetration resistance increases in weeks and months after dynamic compaction. This explanation was suggested very recently in Michalowski (2010), and Michalowski and Nadukuru (2010, 2011). An increase in the horizontal stress was considered earlier by Schmertmann (1987, 1991) as a possible reason for time-dependent increase in cone penetration resistance. The study presented here, indicates stress corrosion cracking and an increase in the elastic moduli as the cause of the horizontal stress increase in the soil bed.

A related phenomenon is well known in structures subjected to cyclic loads. A structure made of elasto-plastic material may respond with irreversible deformation in the first or first few loading cycles, but the response may become purely elastic during subsequent cycles. This phenomenon is known as shakedown (Melan 1938), and it is a result of a residual stress field left in the structure after the first load cycles. The residual stress field is a result of incompatibility of the plastic and elastic strains. If this residual stress field is opposite to the one induced by the cyclic load, then the total stress everywhere in the structure may remain below yield limit, giving an impression of an increased strength. It is, however, the superposition of two stress fields, and not increased material strength. Time delayed increase in cone penetration resistance after dynamic compaction of sands is also a result of the superposition of the load over an existing stress field; this time, however, this is a stress field that changes in time.

CONCLUSIONS

A hypothesis was presented in this paper indicating that the decrease in the cone penetration resistance of sands after dynamic compaction is caused by an increase in the deviatoric stress in the sand bed. Some evidence was presented based on the discrete element simulation. While the numerical evidence may not be convincing, the simulated process of force chains formation after liquefaction is quite plausible. The subsequent increase in the cone penetration resistance in the weeks and months following compaction is due to an increase in horizontal stress in the soil bed caused by an increase in elastic moduli under one-dimensional strain conditions. The latter is caused by static fatigue at inter-granular contacts and grain convergence. Static fatigue is a result of stress corrosion cracking of morphological features at inter-granular contacts.

An increase in the horizontal stress was considered earlier by Schmertmann (1987) and Mesri et al. (1990) as a possible reason for time-dependent increase in cone penetration resistance after dynamic compaction. Stress corrosion cracking and the increase in elastic moduli were considered here as the likely cause of this time-dependent behavior of sand.

ACKNOWLEDGEMENTS

The work presented in this paper was carried out while both authors were supported by the National Science Foundation, grant No. CMMI-0724022, and the first author was supported by the Army Research Office, grant No. W911NF-08-1-0376. This support is greatly appreciated. The authors also would like to thank Itasca Consulting Group for academic license of their PFC3D code, and The University of Michigan Electron Microbeam Analysis Laboratory, for the use of their Quanta 3D Scanning Electron Microscope supported by the National Science Foundation, grant No. DMR-0320740.

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