Predicting Menard Modulus using Dynamic Compaction Induced Subsidence

Babak Hamidi[1], Serge Varaksin[2] and Hamid Nikraz[3]
[1]PhD Candidate, Curtin University
[2]Deputy General Manager, Menard
[3]Head of Department and Professor of Civil Engineering, Curtin University

Synopsis: Previous research by Varaksin et al. [1] suggests that it is possible to develop a relation between strain and increase in Menard Pressuremeter (PMT) limit pressure, whereas limit pressure will double every time the ground is strained strain 3%. Later, Hamidi et al. [2] proposed a new method to predict the limit pressure profile after dynamic compaction with the assumption that induced ground subsidence is the accumulation of vertical strains according to a Rayleigh distribution. Comparison of the geometric mean of predicted and post improvement measured limit pressure values suggest that this method of calculation is quite reliable. Noting that there are also established empirical relationships between the limit pressure and Menard Modulus, it would seem rational that a similar method can be used to predict the Menard modulus. This has been studied in this paper and it can be observed that for practical purposes, this method is able to provide Menard Modulus values of the correct magnitude.

Keywords: dynamic compaction, Menard pressuremeter test, limit pressure, Menard modulus.

1. Introduction

The concept of dynamic compaction is improving the mechanical properties of the soil by transmitting high energy impacts to loose soils that initially have low bearing capacity and high compressibility potentials [3]. The impact creates body and surface waves that propagate in the soil medium. In non-saturated soils the waves displace the soil grains and re-arrange them in a denser configuration. In saturated soils the soil is liquefied and the grains re-arranged in a more compact state. In both cases the decrease of voids will cause the ground surface to subside, and the increase in granular contact will directly lead to improved soil properties.

The depth of influence is the depth where improvement in the soil is no more practically observable (or realistically speaking, more than a certain threshold value). Menard and Broise [4] developed an empirical equation in which the depth of influence was equal to the square root of the impact energy; i.e. the product of the pounder weight (in tons) by the drop height (in metres). Later and based on further site experiences others such as Mayne et al. [5] proposed the introduction of an empirical coefficient to the original equation.

The verification of dynamic compaction can be done through any suitable testing method; however as the late Louis Menard developed both dynamic compaction and the pressuremeter test (PMT) and held their patents for years, PMT is widely used in dynamic compaction projects.

PMT is a field test that measures the deformation properties of the soil in addition to a rupture or limit resistance. It consists of two main elements; i.e. a radially expandable cylindrical probe that is placed inside a borehole at the desired test elevation and a control unit which remains on the ground surface. The probe is made up of three independent cells and consequently exerts a strictly uniform pressure against the surrounding soil cylinder at the central cell level.

During each increment of loading, the ground deformation (volume of the cylinder) is measured and limit pressure (P_l) and Menard Modulus (E_M) are determined. The harmonic mean of P_l and geometric mean of E_M are respectively used to calculate ultimate bearing capacity and settlements [6].

1.1 The Relation between Dynamic Compaction Induced Subsidence and Post Dynamic Compaction Limit Pressure

Varaksin et al. [1] have developed a relation between dynamic compaction induced strain and the improvement of P_l for Al Quoa'a dune sand. In that dynamic compaction project 1.13 million m^2 of dry desert dune sand with a maximum backfill thickness of 28 m was compacted using pounders weighing up to 35 tons [7]. The hypothesis was that for every 3% of strain the soil's limit pressure would double. Thus it could be written in the form of Equation 1.

$$\varepsilon = a \frac{\log\left({(P_l)_j}/{(P_l)_i} \right)}{\log 2} \tag{1}$$

ε= strain
$(P_l)_i$= limit pressure before soil improvement
$(P_l)_j$= limit pressure after soil improvement
a= percentage of strain induced for doubling of the limit pressure (3%)

Further expanding this notion, Hamidi et al. [7] developed a relation between ground subsidence and the increase in limit pressure as presented in Equation 2.

$$s = \sum_{k=1,m} h_k \varepsilon_k = \frac{a}{\log 2} \sum_{k=1,m} h_k \log\left({(P_l)_j}/{(P_l)_i} \right)_k \tag{2}$$

m= number of pressuremeter tests in the borehole within the improvement zone (i.e. the depth where P_l values have increased), and h_k is the testing interval.

Early research by Lukas [8] to more recent works by Bonab and Rezaei [9] indicate that a sickle shape curve characterizes the soil displacement profile along vertical lines of soil. The curves become flatter as they go farther away from the impact centre. From the surface, the bell shaped ground displacement increases and then reduces to a point where movement changes become negligible.

Berry et al. [10] have proposed that for simplicity a Rayleigh distribution be used for void ratio reduction. The probability density function Rayleigh distribution can be mathematically written in the form of Equation 3.

$$\varepsilon(z) = \frac{z}{\sigma^2} e^{-z^2/2\sigma^2} \tag{3}$$

z= depth from surface

σ= depth of maximum strain. Lukas [8] assumes maximum improvement to be at a depth between one third to one half the depth of improvement.

The model that is proposed by Hamidi et al. [2] is subject to the below assumptions:

1. A pressuremeter test has been carried out in the treatment area before dynamic compaction.
2. The material grading in the ground is relatively uniform throughout the treatment depth.
3. The soil parameters are fairly uniform before treatment; i.e. there are no very loose or very dense layers.
4. Average ground settlement is measured; either by levelling the ground using a loader or grader or by using the average measured settlement of the heave and penetration test for the pounder's cell.

Ground subsidence due to dynamic compaction is the accumulation of the vertical deformation of the layers within the depth of improvement. If testing intervals are kept constant it can be said that

$$\sum_{k=1,m} \varepsilon_{DC\_k} = \frac{s}{h} \tag{4}$$

ε_{DC_k}= Dynamic compaction induced strain in layer (testing interval) *k*
h= testing interval

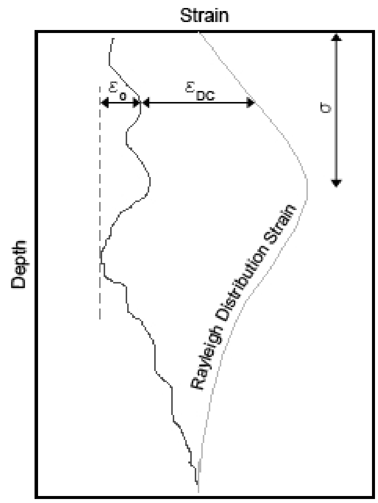


Figure 1: Rayleigh distribution strain as a function of pre-treatment and dynamic compaction induced strain [2]

If all layers had the same initial P_l value, then it could have been said that dynamic compaction induced strain would be the same as the strain that would be in the form of the Rayleigh distribution. However, the limit pressure values will most probably. Thus, a pre-strain, ε_{o_k}, is introduced for each P_l level. This term represents the strain difference between that level and the level with the lowest P_l value. In other words, assuming the pre-treatment loosest soil level as the local origin of computations, it can be imagined that all other layers have undergone a strain to reach their initial pre-treatment state. The summation of ε_{o_k} and ε_{DC_k} will form the Rayleigh distribution strain, ε_R (see Figure 1), formulated into Equation 5.

$$\varepsilon_{o\_k} + \varepsilon_{DC\_k} = \varepsilon_R = c_R \frac{z}{\sigma^2} e^{-z^2/2\sigma^2} \tag{5}$$

c_R= proportion coefficient. Hamidi et al. [2] note that predicted post improvement P_l are very sensitive to the value of σ, and lesser σ values, signifying that strain has been limited in the upper levels of soil, tend to result in unrealistically high limit pressure values at depths around σ. It appears that a value of 0.45 to 0.5 depth of influence can predict more rational peak values for P_l.

ε_{o_k} is not known but can be back calculated by determining how much each level had strained to reach its pre-improvement limit pressure, P_{l_k}, as compared to the minimum pre-treatment limit pressure, P_{l_min}. This calculation can be done using Equation 1, re-written in the form of Equation 6.

$$\varepsilon_{o\_k} = \frac{\log\left({(P_{l\_k})}/{P_{l\_min}} \right)}{\log 2} a \tag{6}$$

Once ε_{o_k} and ε_{DC_k} for each layer has been determined it is possible to add them all up and determine the proportion coefficient:

$$c_R = \frac{\sum \frac{\log\left({(P_{l\_k})}/{P_{l\_min}} \right)}{\log 2} a + \frac{s}{h}}{\sum \frac{z_k}{\sigma^2} e^{-z_k^2/2\sigma^2}} \tag{7}$$

Once c_R has been determined ε_{DC_k} for each layer can be calculated as below:

$$\varepsilon_{DC\_k} = \frac{\sum \frac{\log\left(\left(P_{l\_k}\right)/P_{l\_min}\right)}{\log 2} a + \frac{s}{D}}{\sum \frac{z_k}{\sigma^2} e^{-z_k^2/2\sigma^2}} \frac{z}{\sigma^2} e^{-z^2/2\sigma^2} - \frac{\log\left(\left(P_{l\_k}\right)/P_{l\_min}\right)}{\log 2} a \tag{8}$$

As a final step, the post improvement limit pressure value of each layer can be computed to be equal to:

$$\left(P_{l\_k}\right)_{post} = \left(P_{l\_k}\right)_{pre} 2^{\varepsilon_{DC\_k}/a} \tag{9}$$

It is possible that ε_{DC_k} becomes a negative number. This means that the model is predicting a negative strain or expansion of soil and consequently a reduction in P_l. In such a case a subsequent calculation attempt should be repeated without considering the levels associated with negative ε_{DC_k} values.

Hamidi et al. [2] have shown that it is possible to predict the post treatment geometric mean P_l using the discussed method with an accuracy of 99% if the value of σ is chosen appropriately. As geometric mean values are used in bearing capacity calculations, even if individual point results vary from reality, the difference in bearing capacity calculations would remain within acceptable derivations.

2. The Relation between Dynamic Compaction Induced Subsidence and Post Dynamic compaction Menard Modulus

Menard [6] has identified a correlation between Menard Modulus, E_M and P_l, for different soil types; hence it would seem rational to anticipate that, using a similar approach, it would be possible to predict post dynamic compaction E_M values.

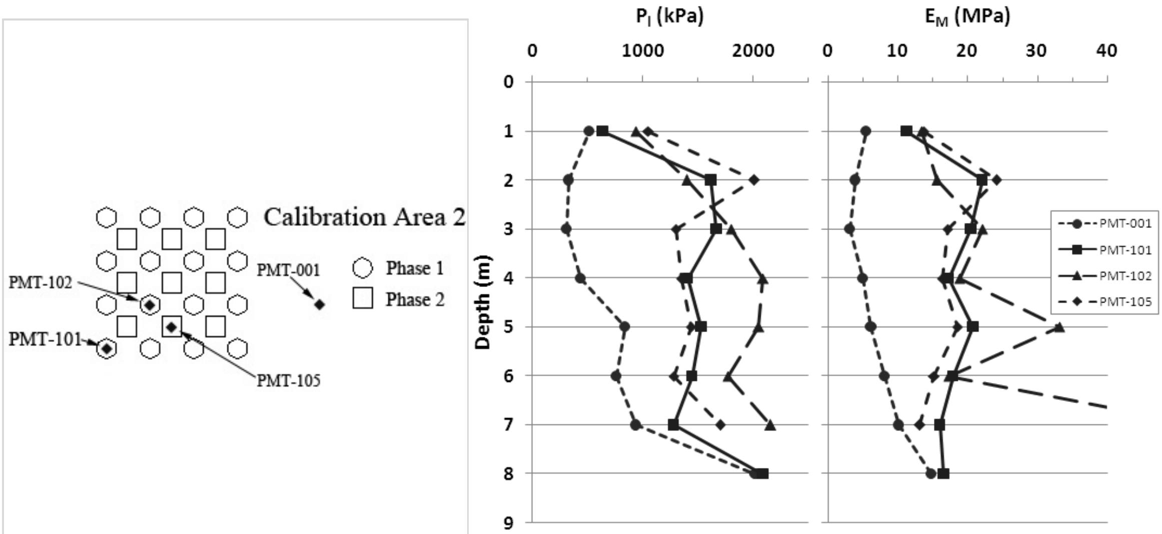
E_M will double in value every time the soil is strained by a certain percentage, *b*, that does not necessarily have to be 3%. Equations 6 to 9 can be re-written in terms of *b* and E_M:

$$\varepsilon_{o\_k} = \frac{\log\left(\left(E_{M\_k}\right)/E_{M\_min}\right)}{\log 2} b \tag{10}$$

$$c_R = \frac{\sum \frac{\log\left(\left(E_{M\_k}\right)/E_{M\_min}\right)}{\log 2} b + \frac{s}{h}}{\sum \frac{z_k}{\sigma^2} e^{-z_k^2/2\sigma^2}} \tag{11}$$

$$\varepsilon_{DC\_k} = \frac{\sum \frac{\log\left(\left(E_{M\_k}\right)/E_{M\_min}\right)}{\log 2} b + \frac{s}{D}}{\sum \frac{z_k}{\sigma^2} e^{-z_k^2/2\sigma^2}} \frac{z}{\sigma^2} e^{-z^2/2\sigma^2} - \frac{\log\left(\left(E_{M\_k}\right)/E_{M\_min}\right)}{\log 2} b \tag{12}$$

$$\left(E_{M\_k}\right)_{post} = \left(E_{M\_k}\right)_{pre} 2^{\varepsilon_{DC\_k}/b} \tag{13}$$



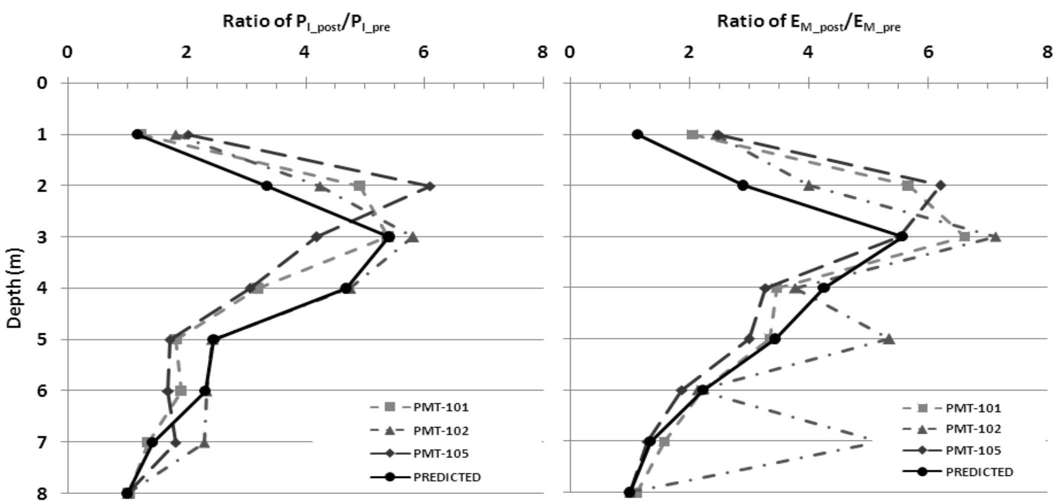
(a) **(b)** **(c)**

Figure 2: (a) Calibration area layout, (b) limit pressures, (c) Menard Moduli

3. Verification

Marjan Island is a 2.7 million m^2 development located 27 km southwest of Ras Al Khaimah in the United Arab Emirates. This project has been reclaimed from the Persian Gulf by tipping sand into the sea. 240,000 m^2 of the development's major road has been subject to treatment by dynamic compaction with the objective of improving the soil parameters down to the depth of about 7 m.

Figure 2(a) shows the layout of the dynamic compaction calibration. A 20 ton pounder was dropped from 20 m in this area. PMT-001 was carried out before ground improvement. After two phases of dynamic compaction the ground was levelled and average subsidence was measured to be 0.29 m. PMT-101 and PMT-102 were performed in two prints of the first phase of compaction, and PMT-105 was performed in one of the prints of phase two. P_l and E_M of these tests are shown in Figure 2(b) and 2(c).



(a) **(b)**

Figure 3: ratios of improvement (a) for limit pressures, (c) for Menard Moduli

While it would have been expected for the improvement profiles to follow sickle shapes similar to the Rayleigh distribution, that is not exactly the case and improvements are more uniform in depth with occasional points of higher strength. Due to the non-classical shape of the improvement profiles it is indeed interesting to see how the proposed method will predict P_l and E_M values.

For calculation purposes it is assumed that depth of improvement was 10 m (any strain in the denser layers at depth has been assumed to be negligible), σ=4.5 m, and a=b=3%. While subsidence calculated P_l values was from 0.27 to 0.34 m which is close to the actual average subsidence, E_M based settlement calculations were larger and from 0.33 to 0.42 m. This is not necessarily inaccurate as all tests were performed in print locations. The greatest difference was observed in PMT-102 with the most fluctuating profile.

For both P_l and E_M predictions, the general shape of the ratio of predicted post improvement parameter (P_l and E_M) to initial value of parameter is quite similar to actual post improvement parameter to initial value of parameter (refer to Figure 3); however the actual harmonic mean P_l is 94% to 117% of predicted harmonic mean of the soil levels. In line with the predicted settlements based on E_M, the actual geometric mean E_M is 112% to 144% of the predicted harmonic mean. It appears that in general the largest variation in the ratios is in the level where improvement is maximum. This may be due to the fact that all tests were carried out in the print itself; however more research is required to confirm this explanation. The biggest difference is once again in PMT-102. A review of E_M to P_l ratios in the post improvement tests shows that the range of values in PMT-102 has had the most amount of variation.

3. Conclusions

Further to the research of Hamidi et al [2] for predicting P_l using dynamic compaction induced subsidence, the same methodology was used to predict P_l and E_M in tests that did not well resemble the expected post treatment sickle shape profile. These tests were all performed in print locations. Predicted harmonic mean P_l in the treatment depth were reliably close to measured harmonic mean P_l values. Back calculated settlement based on measured E_M was more than reality and predicted geometric mean E_M values were less than measured geometric mean values; however the profile shapes were still reasonably similar to reality. The biggest differences between predicted and measured parameters occurred in tests that had the least resemblance to a sickle shape that was modelled using a Rayleigh distribution.

4. References

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