Achieving Improvement with Dynamic Replacement Stone Columns-Impact Crater Depth-Capacity Evaluation

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Achieving Improvement with Dynamic Replacement Stone Columns – Impact Crater Depth -Capacity Evaluation

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Abstract

Dynamic replacement penetration tests, with both the Dynamic Compaction (DC) and Rapid Impact Compaction (RIC) methods, have been carried out on three sites in South Africa on variable ground profiles. Quality assurance is normally done by means of plate load tests on selected stone columns and a limit is typically placed on the acceptable deformation modulus, for the Engineer to approve works. The results from the penetration tests are presented, with a comparison of the achieved deformation moduli. A method is developed, based on impact engineering formulation, taking into consideration drop height and pounder weight and shape to predict the deformation modulus that would be achieved for a certain penetration depth.

Keywords: *Ground improvement, Experimental analysis, Dynamic Replacement Stone columns, Penetration Testing, Plate load test*

1 Introduction

Dynamic Compaction- and Rapid Impact compaction- replacement techniques are often used to improve the bearing and settlement/stiffness characteristics below structures or to choke cavities in dolomitic profiles. If used below a structure or fill, the stone columns are normally designed as a piled raft and capped with a high strength geotextile and a load transfer granular raft. Quality assurance may include the use of plate load tests to establish the Young’s Modulus of the stone columns, exposing some stone columns to confirm penetration depth, DPSH testing between the stone columns, as well as Continuous Surface Wave (CSW) testing on the completed granular raft.

Stone column depths can normally be crudely estimated by the amount of dumprock used to create the stone column divided by the pounder cross sectional area used and is largely dependent on the in situ densities of the materials found on site.

To ensure the design capacities of these dynamic replacement stone columns have been achieved, plate load tests are normally undertaken on some of the installed columns. The designer will set specific performance criterium in terms of a Young's modulus which is determined from stress and displacement measurement. The contractor normally sits with the dilemma that the Young's modulus measured is lower than the required value set out in the project specification and having to recompact the impact positions. The contractor and the consultant alike therefore requires a means by which he can correlate the set (mm/blow) achieved to a Young's Modulus, before undertaking the plate load test. This paper serves to illustrate a method by which the contractor can calculate the set required to achieve a certain Young's modulus.

Three sites; one on a dolomitic profile in Olifantsfontein in Gauteng, one on aeolian clayey sand (Berea Red Sand) in Durban and one on an alluvial clayey silt also in Durban were assessed to establish the set (mm/blow) required to achieve a specified Young's Modulus for both the RIC and DC methods.

2 Impact Physics

In a collision of two ordinary objects, both objects are normally deformed, often considerably, because of the large forces involved. When the collision occurs, the force usually jumps from zero at the moment of contact to a very large value within a very short time, and then abruptly returns to zero (Giancoli, 2000). With the dynamic replacement method the impact weight is non-deformable whilst the soils deform.

2.1 Dynamic Replacement with the Dynamic compaction method

Dynamic Replacement with the Dynamic compaction method is normally achieved by dropping a +/-1.0m diameter, 12 tonne weight from a height of 18m at less than 1 blow per minute.

The velocity of the weight just before impact will be:

$$v = \sqrt{2g(y_0\text{-}y)} = 18.7\text{m/s}. \quad (1)$$

As the weight hits the ground, the momentum is quickly brought to zero. The Impulse on the weight is:

$$\begin{aligned} J = F\Delta t = \Delta p &= p_f - p_i \\ &= 0 - (12000\text{kg})(18.7)\text{m/s}) = -224\ 400\ \text{N.s} \end{aligned} \quad (2)$$

In coming to rest, the body decelerates from 18.7m/s to zero over a certain distance, X, the penetration depth. The average speed during this brief period is:

$$v = (18.7\text{m/s} + 0\text{m/s})/2 = 9.35\ \text{m/s}. \quad (3)$$

So, the collision time lasts:

$$\Delta t = \frac{d}{v} = 0.106X\ \text{s}. \quad (4)$$

Since the magnitude of the impulse is $F\Delta t$ = 224 4400 N.s and Δt = 0.106Xs, the average net force F has magnitude:

$$F = \frac{J}{t} = 2\ 116\ 981X^{-1}\ \text{N}. \quad (5)$$

F is the sum of the average force upwards (Newton's second law) on the impact mass exerted by the ground, F_{grd}, which we take as positive plus the downward force of gravity, -mg:

$$F = F_{grd} - mg \tag{6}$$

When reviewing the above calculation Figure 1 summarises the force exerted by the ground, F_{grd}, on the impact mass for various values of X. Young's Modulus values, derived from F_{grd}, the pounder cross section and impact deflections are also summarised. A discussion on these Young's moduli follows later in Section 2.2.

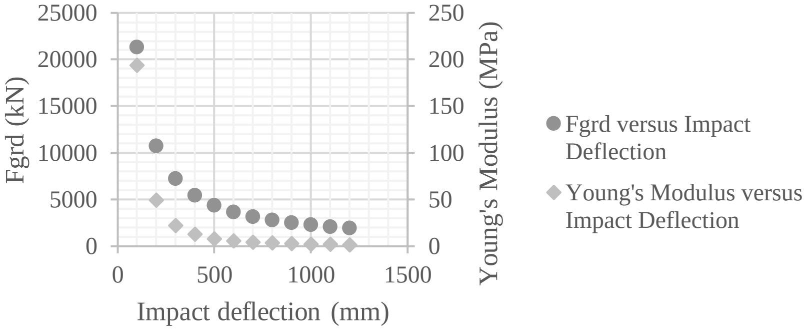

Figure 1. DC replacement

From the above and when considering shear strain the shear strains are normally at levels exceeding about 7.5%. These values are much larger than the typical shear strain ranges expected from a plate load test to the failure load.

2.2 Dynamic Replacement with the Rapid Impact Compaction method

Dynamic Replacement with the Rapid Impact compaction method is normally achieved by dropping a +/-1.0m diameter 9 ton weight from a height of 1.5m at 40–60 blows per minute.

If the same discussion is followed as per Section 2.1, Figure 2 is derived.

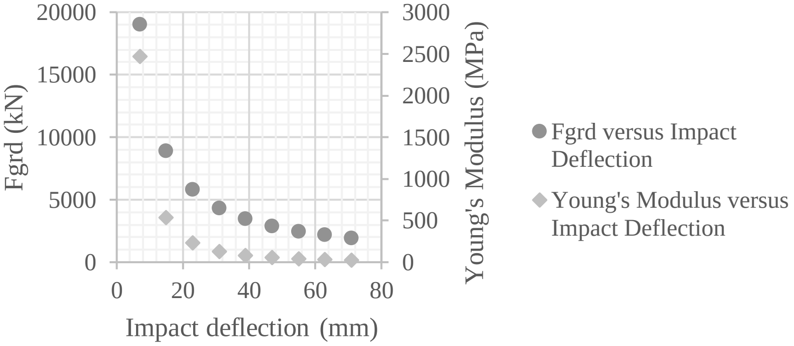

Figure 2. RIC replacement

From Figure 2 it can be concluded that shear strains are at ranges exceeding about 0.5%, and therefore closer to the shear strain ranges of a plate load test.

Based on the above to achieve similar F_{grd} one can conclude the ratio for RIC to DC impact deflections is some 0.06. One can conclude by comparing the Young's Moduli derived that the values are subjected as for the same F_{grd} the crater depths and associated shear strains vary due to the actual impact energy and therefore with the RIC method results in much higher Young's Moduli values when compared to the DC method. These values also does not compare well to values measured on site, even for the RIC which has similar shear strains when compared to a conventioal plate load test. Other theories were therefore assesed to establish if one can derive a correlation between the set (mm/blow) and the expected Young's Modulus from the plate load test.

3 Young's Modulus required

When reviewing a settlement and bearing problem holistically one normally needs to improve the cumulative Young's modulus below the structure to a depth equivalent to about two times the breath of the structure. In other words, Dynamic Compaction in a deep and a homogeneously weak profile can be considered below structures with a width of about 3m. The stone columns, driven in a grid pattern into the subgrade, will stiffen the profile whilst also stiffening the soils between and below such columns. If the profile is only weak in the top 6–7m's, Dynamic replacement stone columns with a granular raft can also be considered to improve these top layers as shown in Figure 3.

One can consider stone columns as driven short piles, although not entirely true as the stone would not consist any cohesion, and consider the plate load test to act as a type of pile load test in which one can establish the Young's Modulus or settlement behaviour. Stone columns can normally be installed to some 3.5—4.5m depth with the dynamic replacement methods depending on the soil profile and is normally spaced with methods as described by Oshima and Takada (1997). One can review the raft with piling raft formulations but one can also look at the raft and establish the cumulative improvement in Young's Modulus required to deal with the structure.

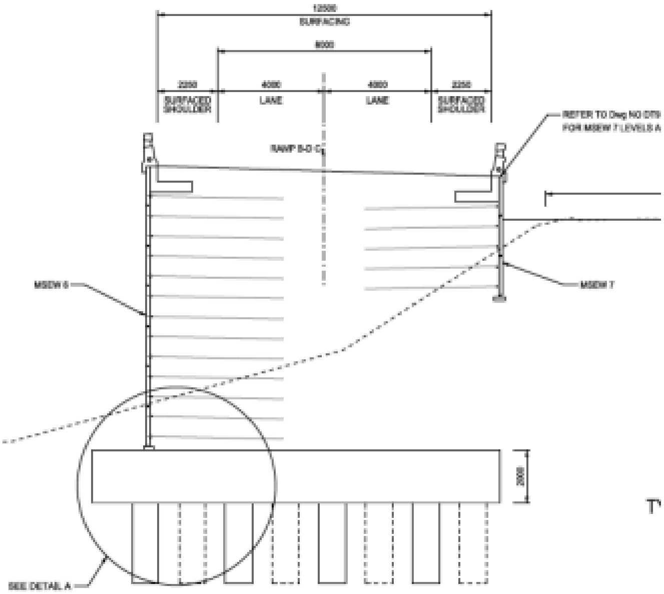

Figure 3. Piled stone column raft below MSEW structure

The MSEW structures at the Mt Edgecombe Interchange and Cornubia Blackburn link bridge both had very low SPT-N blowcounts in the top 5–7m as well as a clay profile at the Mt Edgecombe I/C. The improved soil profile with dynamic replacement stone columns and granular raft were modelled in finite element software to establish the effect of such soil improvement on the behaviour of the structure.

4 Penetration law

Li and Chen (2003) as taken from Pichler et al (2004) describes the penetration law for rock boulders hitting gravel as with formulae describing the penetration depth as follows:

$$\frac{X}{d} = \sqrt{\frac{1+k\pi/4N}{(1+\frac{1}{N})\pi}} \qquad \text{for } \frac{X}{d} \leq k\text{, or} \qquad (7)$$

$$\frac{X}{d} = \frac{2}{\pi} N \ln \frac{1+1/N}{(1+k\pi/4N)} + k \qquad \text{for } \frac{X}{d} > k. \qquad (8)$$

Where:
X = penetration depth
d = diameter of the impactor

N is a geometry function characterizing the sharpness of the impactor nose, I is the impact function describing the intensity of the impact, and k is the dimensionless depth of a surface crater.

The geometry function N is defined as:

$$N = \frac{m}{\rho s d^3 B N^*} \qquad (9)$$

Where
m = mass of the impactor,
ρ_s = mass density of the target material,
B = dimensionless compressibility parameter of the impacted material (1.2 can be used for gravels),
N* = nose shape factor = $\frac{1}{1+4\psi^2}$ where $\psi = \frac{H}{d}$ (See Figure 4)

The impact function I is defined as:

$$I = \frac{mv}{Rd^3} \qquad (10)$$

where
R = strength-like indentation resistance of target materials.

The dimensionless depth of the surface crater, k, can be defined as follows:

$$k = 0.707 + \frac{H}{d}. \qquad (11)$$

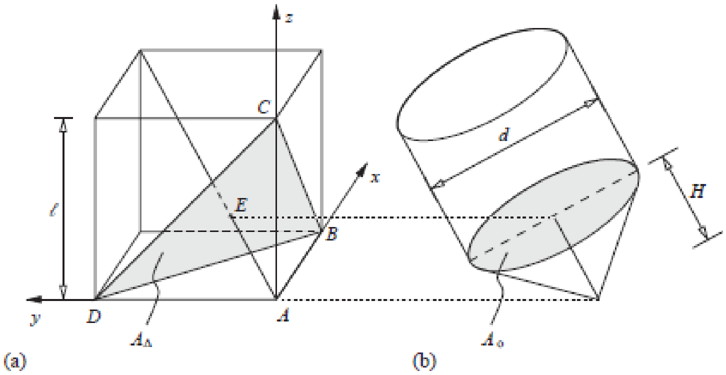

Figure 4. a) Cubic Impactor with pyramidal nose
Figure 4. b) equivalent impactor with conical nose (Pichler, 2004)

5 Plate Load Test

Plate load tests are normally requested on completed dynamic replacement stone columns to establish if a sufficient improvement has been achieved.

The designer must decide what Young's modulus value is required to deal with the holistic problem at hand.

Normally Wrench's (1984) equation is specified to determine the Young's Modulus of the stone columns from the plate load test results:

$$E = \frac{(1-v^2)\pi r\sigma}{2p} \qquad (12)$$

Where:
v = Poisson's ratio,
R = radius of the plate,
σ = applied stress (kPa),
p =deflection (mm).

It is normally requested that the plate be loaded to half the required stress whereafter the Young's Modulus be measured on a reload cycle ensure that all loose materials settles and does not obscure the results.

Assuming the plate is 1000mm diameter and an influence zone of some 2D, for a Young's Modulus of 50MPa a shear strain of $1.5\varepsilon_a$ would be around 0.35%, similarly for impact loading with the Dynamic Compaction method the shear strain will be around >7.5% and roughly estimated to be from Figure 5 half to a third of the modulus at 0.35% shear strain. For the RIC method the shear strain will be >0.5% and probably around half the modulus at 0.35% shear strain. This modulus at large shear strains is believed to be the strength-like indentation resistance of the target material, R, as described by Li and Chen (2003).

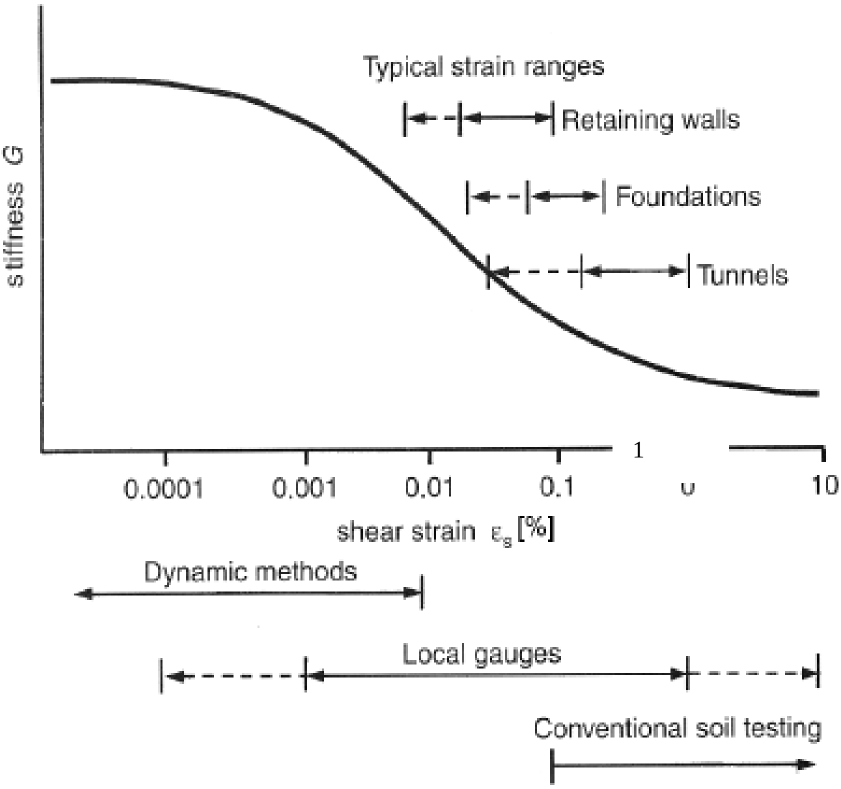

Figure 5. Characteristic stiffness-strain behaviour of soils with typical ranges for laboratory and structures (Mair, 1993)

The three sites where dynamic replacement were undertaken will be discussed in further sections. In these sections a penetration depth is derived from Li and Chen's formulation and compared to Young's Moduli derived from the plate load test and compared to actual penetration values measured.

6 Olifantsfontein (R21)

Olifantsfontein involved the chocking of cavities in a dolomitic profile on the R21 with the DC replacement method. A Young's modulus of 50MPa was specified but the contactor exceeded this value with average Young's Moduli in the range of 125MPa.

Table 1 compares the estimated and measured set using a factor of three between he Young's Modulus from the plate load and R.

Table 1. Comparison between measured set and Li and Chen estimated set at the Olifantsfontein site

Sample ID	Young's Modulus (MPa)	Final Set (mm/blow)	Estimated Set (mm/blow)
1	124	150	190
2	87	170	270
3	149	140	160
4	137	180	170

The Mean Absolute Error (MAE) is estimated to be 42.5mm/blow larger than the actual final set achieved. The MAE can in all likelihood be attributed to the factor that was assumed between the Young's Modulus and R used in Li and Chen's formulation and measurement tolerance during the surveying of the set which was undertaken after every two blows. It can therefore conservatively be assumed that a set of around 160mm/blow with the dynamic compaction-dynamic replacement method should result in an equivalent Young's modulus of around 125MPa.

7 Cornubia Bridge Blackburn Link

Cornubia Bridge involved the construction of 10m high tiered MSEW on a very weak profile to some 5m below the investigation NGL with characteristic cautious estimate SPT-N values of around 7. Stone columns were therefore required to improve this weak layer whilst stiffening the foundation. The dynamic replacement was undertaken with the RIC method and Young's Moduli specified as 50MPa on the stone columns.

A factor of 2.5 was used between the Young's Modulus from the plate load to R.

Table 2. Comparison between measured set and Li and Chen estimated set at the Cornubia Bridge site

Sample ID	Young's Modulus (MPa)	Final Set (mm/blow)	Estimated Set (mm/blow)
1	71	26	16
2	93	23	13
3	90	24	13
4	100	20	12
5	45	19	25

The Mean Absolute Error (MAE) is estimated to be 6.6mm/blow smaller than the actual final set achieved. The RIC rig however has on-board set measuring equipment and should therefore be fairly accurate.

8 Mt Edgecombe Site

Mt Edgecombe I/C site has numerous MSEW, some up to 17m high with a loose profile and black clays under some of the walls up to about 6m depth. Stone columns were therefore required to improve this weak layer whilst stiffening the foundation and acting as a wick drain in the black clays. The dynamic replacement was undertaken with the DC method and Young's Moduli specified as 50MPa on the stone columns.

Table 3 compares the estimated and measured set using a factor of three between the Young's Modulus from the plate load and R.

Table 3. Comparison between measured set and Li and Chen estimated set at the Mt Edgecombe I/C site

Sample ID	**Young's Modulus (MPa)**	**Final Set (mm/blow)**	**Estimated Set (mm/blow)**
1	151	218	160
2	116	121	210
3	140	253	170
4	82	159	290
5	35	351	670
6	65	239	368

The Mean Absolute Error (MAE) is estimated to be 134mm/blow larger than the actual final set achieved. This can likely be attributed to the surveying tolerances and bulging of the profile and the factor placed on the Young's modulus.

9 Conclusion

Conventional impact physics to establish the force exerted by the ground on a pounder mass has shown little success in deriving a Young's modulus value that can be compared to that derived from the plate load test. The method proposed in this paper, to establish the required set to achieve Young's modulus derived from a plate load test, has been used successfully on three projects in South Africa for both the DC and RIC method with only minor discrepancies being noted between the predicted Young's modulus and the set achieved. These discrepancies can likely be attributed to surveying accuracy and the factor used between the Young's modulus derived by the plate load test and the strength-like indentation resistance, R used by Li and Chen. It is therefore recommended that a factor of two be used on the R in Li and Chen's formulation to determine with a good degree of accuracy what set is required to achieve a certain Young's modulus value from the plate load test undertaken on stone columns. The reader is additionally advised to take cognizance of the actual pounder geometry, weight and drop height being used by the contractor on site.

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