A REVIEW OF IMPACT ORIENTED GROUND IMPROVEMENT TECHNIQUES

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ABSTRACT

Nowadays various ground improvement by impact techniques are widely practiced as technical and economical solutions however each technique has its own use and range of application. It has come to the attention of the authors that the name of one of the techniques; i.e. Dynamic Compaction is being used generically in lieu of the proper names of the other methods. This article will review Dynamic Compaction and shall compare it with two other impact techniques i.e. Rapid Impact Compaction and Impact Roller Compaction. As a conclusion the readers are advised to use the correct terminology to avoid misunderstanding and confusion in projects and results.

1 A REVIEW OF DYNAMIC COMPACTION

Louis Menard invented and promoted Dynamic Compaction (DC) as early as 1969 but it was not until 29 May 1970 that he officially patented his invention in France. The technique was later also patented in many other countries, including Australia in 1981.

The concept of this technique 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. 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 and increase in inner granular contact will directly lead to improved soil properties.

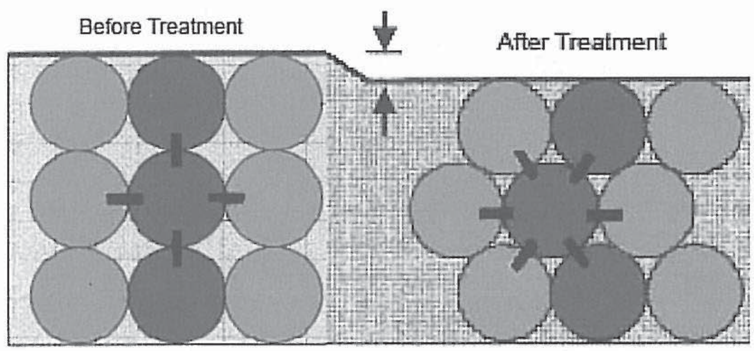

Figure 1 : Displacement and rearrangement of the soil grains in a denser configuration.

The impact energy is delivered by dropping a *heavy* weight or pounder from a *significant* height. The pounder weight is most often in the range of 8 to 25 tons although lighter or heavier weights are occasionally used. The current pounder weight record was set at 170 tons in 1978 with the Menard Giga machine during the ground improvement works of Nice Airport in France (Gambin, 1983). Drop heights are usually in the range of 10 to 20 m although 40 ton pounders have been dropped from 40 m by Menard's Mega machine (Mayne and Jones, 1984).

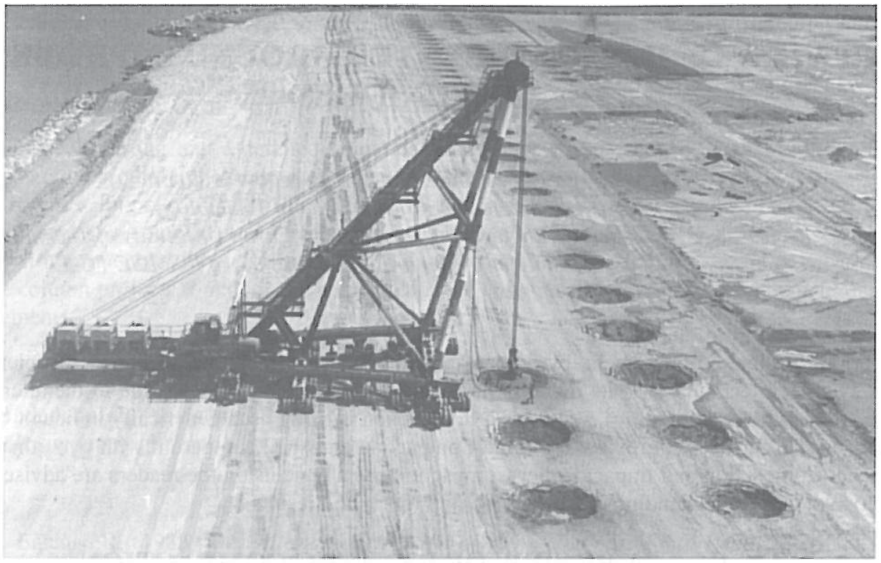

Figure 2: Menard Giga Machine lifting a 170 ton pounder at Nice International Airport (Menard).

Obviously, the most efficient impact is when the pounder is dropped in free fall and there is no energy loss due to the friction of the cable on the sheaves and the hoist drum however the reconnection of the pounder to the lifting equipment may be very time consuming. While the personal experience of the authors suggests that one DC cycle takes less than a minute, the reconnection process may increase this time to more than 5 minutes. Furthermore, the sudden release of the pounder will cause a crane's boom to spring back and the hook block to strike the boom. This impact may damage the lattice network of the boom beyond repair.

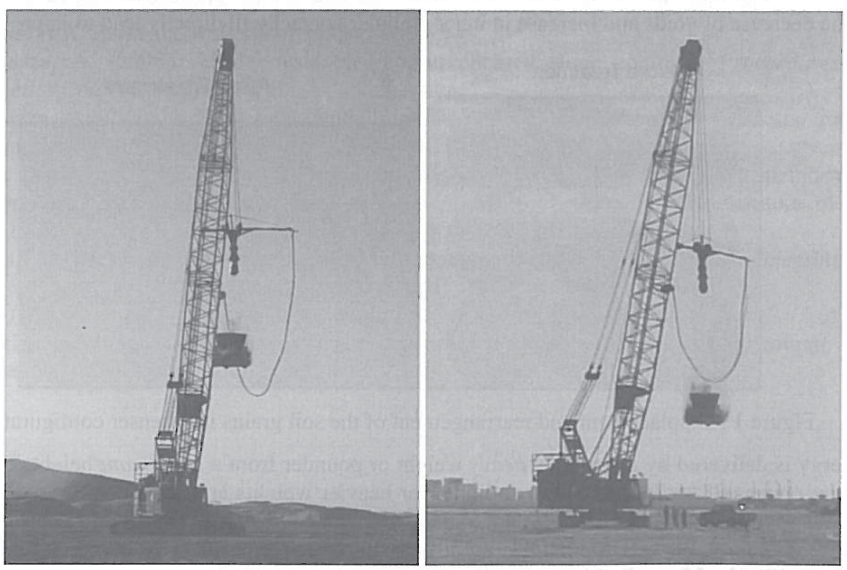

Figure 3: MARS dropping a 35 ton pounder in free fall in Al Quoa, UAE (Menard).

Although efficient freefall was previously possible with the Giga and Mega machines, this efficiency without the mentioned limitations has become possible for modified cranes since 2004 with the introduction of the innovative MARS (Menard Automatic Release System) system which was first used for dropping a 35 ton pounder during the ground improvement works of the 1,100,000 m^2 Al Quoa township project in the UAE. This system was also later used for the pre-collapse of sinkholes and cavities in Germany's Federal Highway BAB A71 (Chaumeny *et al.*, 2008).

The depth of influence is the depth where there is no more observable improvement in the soil. Menard and Broise (1975) developed an empirical equation in which the depth of influence, D, was equal to the square root of the impact energy i.e. the product of the pounder weight (*W* in tons) by the drop height (*H* in meters). Later (Mayne and Jones, 1984) and based on further site experiences it was proposed to introduce a coefficient, c, to the original equation; thus:

$$D = c\sqrt{\frac{WH}{10}}$$

c is usually taken to be from 0.9 to a conservative value of 0.5 based on the ground conditions and equipment. As an example it can be assumed that dropping a 15 ton pounder from 20 m with *c*= 0.7 will have an improvement depth of about 12 m. Dropping the same pounder from 1.2 m or 0.25 m will respectively influence the upper 3 m or 1.4 m of soil. This simple example demonstrates that among other parameters, the concept and success of dynamic compaction at depth is the ability to drop a sufficiently heavy weight from a sufficient height properly.

Dynamic Compaction is usually used to treat loose soils as thick as 15 m however the treatment thickness of Nice Airport was 40 m (Gambin, 1983). In Al Quoa 28 m of soil had to be treated for self bearing (Varaksin *et al.*, 2005).

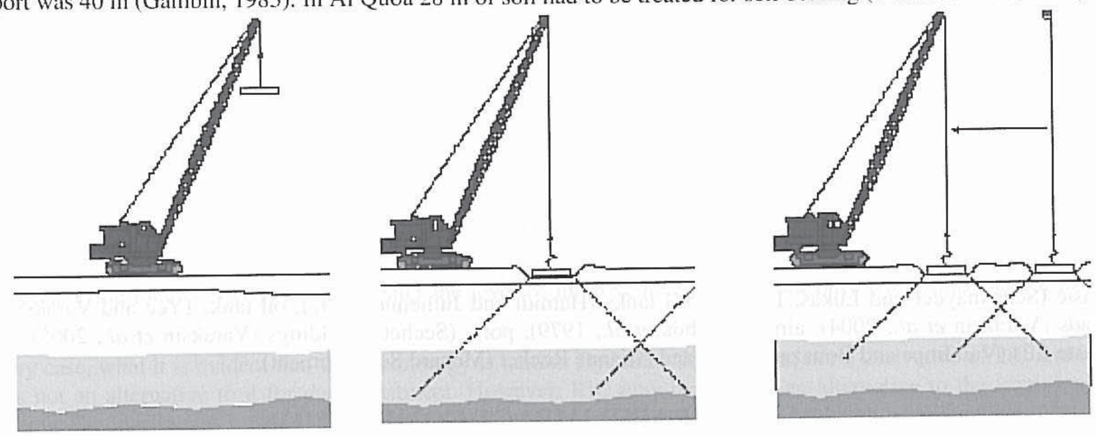

Figure 4: Application of Dynamic Compaction in phases.

Applying Dynamic Compaction in phases is a more efficient treatment method than dropping the pounder contiguously. The initial phase of treatment is carried out at a wide grid with the maximum amount of impact energy or drops per impact point (print). The objective of this phase is to treat the deepest soil layers. The second phase which intends to treat the intermediate soil layer may be carried out with less energy or drops. If necessary, the final phase (ironing) will comprise of closely spaced grid points with one or two blows per print for improving the upper soil layer.

Lukas (1986) has categorised the soil into three zones of improvement based on the soil's grading i.e. the pervious soils, the semi pervious soils and the impervious soils. In saturated soils the best efficiency and results can be expected in the first zone however Dynamic Compaction has been used in almost all types of ground conditions, whether for causing pre-collapse in sinkholes and cavities (Chaumeny *et al.*, 2008), compacting large diameter boulders (Menard Soltraitement, 1978), dune sand (Varaksin *et al.*, 2004), collapsible soil (Rollins and Rogers, 1998), or even consolidating clay (Perucho and Olalla, 2006). DC can be used in combination with other techniques such as with wick drains (Cognon *et al.*, 1983) or surcharging (Menard Soltraitement, 2004) to increase the treatment efficiency.

At first glance, it seems against conventional theories that saturated clays could be improved with Dynamic Compaction. The impact load is transient and applied to the ground in a fraction of a second (Mayne and Jones, 1983). There is no preload and surcharge. In saturated grounds the impact will increase the pore pressure to the point where the soil will liquefy. The pressure will gradually decrease but this process may take weeks in saturated clay.

The process of dynamically consolidating clay cannot be explained by the classical consolidation theory (Terzaghi, 1925) as the assumptions of that theory do not hold for dynamic loads. However, the process has been explained (Menard and Broise, 1975) by noting the compressibility of the small amount of micro bubbles in the saturated soil, the process of liquefaction, the pronounced increase of permeability due to soil fissuring and thixotropy.

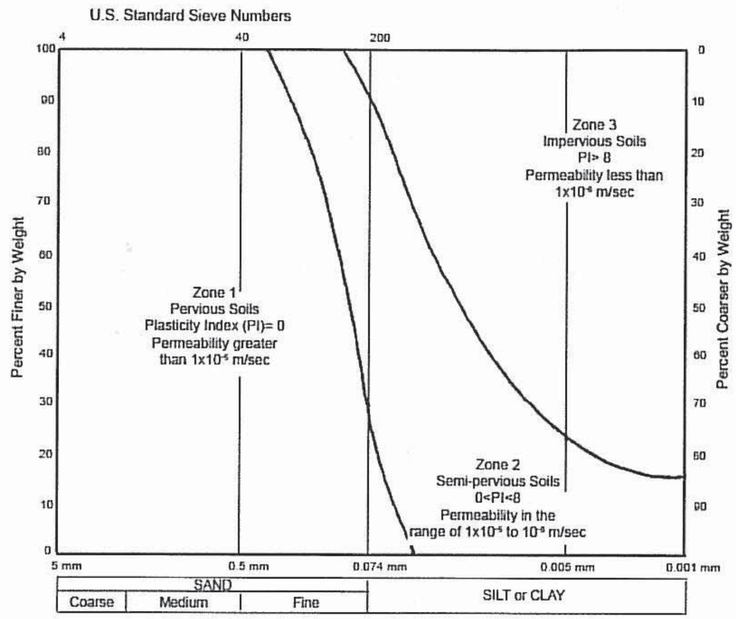

Figure 5: Categorising of soils for Dynamic Compaction (Lukas, 1986).

Dynamic Compaction and Dynamic Replacement have been used in many different applications such as for nuclear waste (Schexnayder and Lukas, 1992), LNG tanks (Hamidi and Jullienne, 2007), oil tanks (Yee and Varaksin, 2007), roads (Varaksin *et al.*, 2004), airports (Choa *et al.*, 1979), ports (Sechet), buildings (Varaksin *et al.*, 2005), domestic waste fills (Van Impe and Bouazza, 1996) and Arianne Rocket (Menard Soltraitement).

2 RAPID IMPACT COMPACTION

According to its website (British Steel Piling (BSP)), the Rapid Impact Compactor (RIC) was developed in the early 1990s by BSP in conjunction with the British Military as a means of quickly repairing damaged aircraft runways. Dynamic energy is imparted by a weight dropping from a controlled height onto a steel foot that has a 1.5 m diameter. Energy is transferred to the ground safely and efficiently as the RIC's foot remains in contact with the ground and no flying debris is ejected.

As compared to Dynamic Compaction, instead of dropping a heavy weight from a great height once or twice a minute, the RIC drops a lighter weight, (5, 7 or 9 tons), from a relatively lower height (up to 1.2 m) at a rate of 40 to 60 times per minute.

The primary usage of RIC in the UK is for shallow compaction of floor slab and roadway subgrades (Terra Systems) however the introduction of this technology in other countries such as the United States and Australia has been associated with a degree of confusion as the technique is sometimes mistakenly referred to by terms other than its proper name, such as dynamic compaction, light dynamic compaction or rapid dynamic compaction. It is true that RIC is also based on impact energy, vibration and consequently the densification of soil grains but the process is not Dynamic Compaction. It is Rapid Impact Compaction.

Disregarding the energy loss due to having to overcome the inertia of the plate resting on the ground and by applying Equation 1 it can be observed that the depth of improvement for a 9 ton weight dropped from 1.2 m with a coefficient of 0.7 will be 2.3 meters. A higher coefficient will yield a somewhat deeper influence depth. With a coefficient of 0.9 the depth of improvement will increase to about 3 metres. It can be observed that while larger depths of improvement have occasionally been reported, these figures are quite compatible with the original purpose of developing the RIC technology and should generally satisfy FAA (1995) requirements for the compaction of subgrade soil in airports.

Figure 6: RIC9000 at work in Asaluyeh, Iran (BSP).

According to Terra Systems research funded by the Federal Highway Administration (FHWA) it has been shown that after about 3 to 4 drops, the depth of improvement does not increase with the number of drops per impact point. Therefore dropping the weight up to 30 or 40 times will improve the degree of treatment but not the compaction depth. The greater the total energy used, the greater the level of improvement will be, but only within the zone of maximum influence.

In any case, what it is evident that this technology is neither Dynamic Compaction, nor a derivative of DC and in many cases not an alternative to it for deep treatment. However, RIC may be used as an alternative to the ironing phase of Dynamic Compaction, as it was done as part of the ground improvement works of Asaluyeh petrochemical plants in Iran (Sazeh Pardazi Iran, 2005).

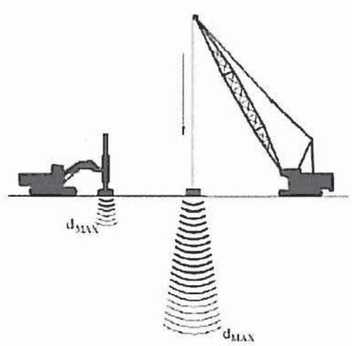

Figure 7: Comparison of improvement depth of Dynamic Compaction and Rapid Impact Compaction (Terra Systems).

3 IMPACT ROLLER COMPACTION

Classical circular roller compactors are capable of compacting 20 to 30 cm of graded soil however sometimes the treatment thickness may be substantially more and a considerable amount of time, money and carbon emissions will be needed to treat the soil.

The idea of improving the treatment thickness by implementing non-cylindrical multisided geometrical rollers was first recognized and patented in 1935 in Sweden, but it was only 20 years later and in South Africa when the impact roller compaction was developed (Avalle, 2004).

Today, impact roller compactors, also sometimes called impact compactors, weigh 8 to 16 tons, have 3 to 5 sides and the practical speed of an Impact Roller is in the range of 8 to 11km/hr depending on the ground conditions (Geoquip). When travelling speed exceeds 11km/hr the drum begins to skip as the drum revolution increases. The drum tends to act with less impact and eventually will run as a circular wheel given sufficient RPM. Impact rollers do not have a motorised form of energy such as the vibratory roller and derive their energy by turning on their corner and falling onto the flat side.

The number of sides of an Impact Roller affects its energy rating. Since an Impact Roller turns on its corner and falls onto its flat side, the greater the difference of these radii the greater the lift height. Three sided rollers produce the maximum lift while five sided rollers produce the least lift (Geoquip). According to Geoquip lifts are from 0.15 to 0.23 m.

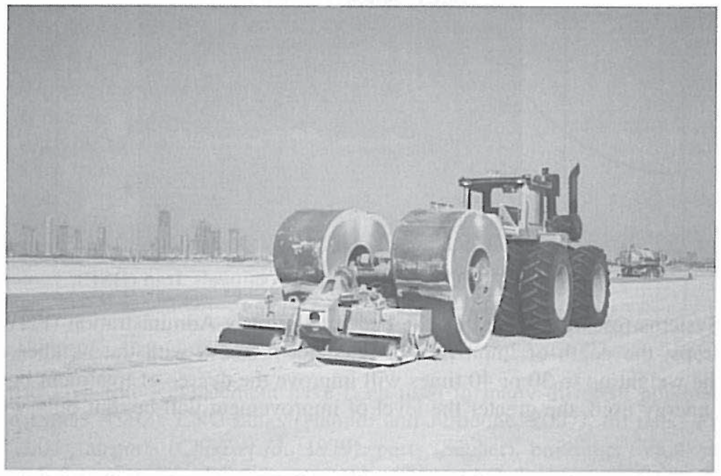

Figure 8: Impact Roller Compaction, Palm Diera - UAE (Landpac).

Impact Roller Compaction is sometimes also erroneously referred to as Dynamic Compaction. This may have happened as a result of an effort by some engineers who were trying to rectify the confusion of using the term roller for a compactor that is in fact not circular in shape. Perhaps this is why Landpac calls the technology Impact Compaction. However, what is clear is that this technology both rolls and has an impact and the original chosen name is able to make a proper distinction for the technique. Hence it is best to respect the correct and existing terminology and not to use the name of one technique for another.

It is interesting to comprehend that abusing a valuable technology may eventually lead to dissatisfaction and mistrust and consequently to its elimination. This has well been understood by the manufacturers and promoters of Impact Compaction who do not want myths to tarnish their products. On its website, Landpac (Typical Myths About Impact Compaction) points out that:

"... Impact Compaction (IC) and Dynamic Compaction (DC) have some very different characteristics that make them distinct from one another.

DC is performed through a very large parcel of energy being imparted over a very short time duration by means of a heavy pounder dropped from a great height onto the soil. The repetition of such compaction cycles is performed at a very low frequency.

IC on the other hand is performed through a far smaller parcel of energy being imparted to the soil over a much greater time duration by means of an eccentrically shaped mass rolling over the soil. The repetition of these compaction cycles is performed at a far greater frequency that DC."

Even though Impact Roller Compaction is not Dynamic Compaction and the authors also agree that it is subject to controversy, for the purpose of demonstration it can be observed that by applying Equation 1 the depth of improvement for an 11 ton weight dropped from 0.23 m with a coefficient of 0.7 will be 1.1 metres. With a coefficient of 0.9 the depth of improvement will increase to about 1.4 metres. While larger depths of improvement have been reported, these figures are quite compatible with the original purpose of developing the Impact Compaction technology i.e. improving the efficiency of roller compaction by thickening the lift height.

Based on the tests that they had performed with Impact Roller Compaction in South Africa, Berry *et al.* (2004) have proposed an alternative method for predicting the profile of improvement in unsaturated soils based on the measurement of ground settlements and a distribution of plastic strains similar to an adapted Schmertmann strain influence diagram. According to this study the improvement depth is 2 to 3 times the compactor's width (900 mm) and the maximum improvement is achieved at about 0.67 to 1 times the compactor's width. This will yield an improvement depth of 1.8 to 2.7 m.

As for the case of the RIC, the Impact Compactor can also be used for improving the superficial layer after ground improvement works, as it has been done after vibrocompaction works at Dubai's Palm Diera project (Landpac).

4 CONCLUSION

Three impact oriented techniques have been discussed in this article. All three techniques are viable for the objectives for which they were developed and use the principle of impact energy to compact the soil. Dynamic Compaction is a technique that implements heavy pounders that are dropped from significant heights. On the contrary, Rapid Impact Compaction and Impact Roller Compaction utilize lighter weights that are dropped from significantly lesser heights. However, the number of impacts per unit of time is much more than Dynamic Compaction. Dynamic Compaction can treat deep soils. The two latter techniques are suitable for treating soils as thick as 2 to 3 metres and may be used in lieu of the ironing phase of Dynamic Compaction.

It is recommended that engineers promote the correct terminology of each of these techniques for although they do share common principles, they have been developed for different objectives and renaming or misusing the names of the techniques can create unnecessary confusion and ultimately undesirable improvement results.

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