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Mechanism of Dynamic Consolidation and Its Environmental Effect

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SYNOPSIS This paper is contributed as case histories in ground soil improvement with particular emphasis of dynamic consolidation. The authors try to present as much as they got from the field testings and observations including vibrational parameters, pore pressures, stereoscopic photogrammetry, etc. in order to trace the real behaviour of ground movement during tamping. It is believed that all the data got from the field work are rather informative and illustrative than that from theoretical modelling in the laboratory. Thus, some highlights relating effective thickness of compaction, maximum spacing between compaction points, number of blows for optimum tamping and seismic attenuation for environmental consideration are given.

I. BACKGROUND

Since 1970, dynamic consolidation as developed by Louis Menard (1) has been used with increasing interest all over the world. Many experiences in various project show that heavy tamping of this technique merits a lot in making soil more compacted and the mechanical properties of the soil to be compacted can be improved with satisfactory result.

However, in the popularization of dynamic consolidation, theoretical approach to its mechanism has remained comparatively less than practice. The only remarkable analysis is running a dynamic loading test by putting soil sample in a consolidation apparatus in the laboratory.(2) But very few work has been done so far regarding the actual behavior of ground soil at the compaction point and in its vicinity during tamping. From practical point of view, field observations of the real behavior of soil may be much meaningful because the design of dynamic consolidation process is necessarily based on these information. So the design of dynamic consolidation as an engineering practice has to make up necessary criteria such as spacing of tamping point, effective depth of compaction to be expected and number of tamping blow necessary to achieve optimum compaction, etc.

In view of the above mentioned situation, the authors have been involved in the mechanism analysis highlighted by field observations and instrumentations in many projects. To this ends, various kinds of soils on different sites of project were tested as prototypes. Further, vibration propagation to adjacent surface structures due to heavy tamping may be destructive as an environmental hazard. So the designers have to keep the compaction point certain distance away from structures concerned.

In this paper, these headlines mentioned above will be introduced and discussed in the sense of designing dynamic consolidation for a project.

II. OVERVIEW OF SOIL CONDITIONS AND FIELD INSTRUMENTATIONS

1. Ground Soil Conditions

Different sites in Beijing, Hebei, Shandong provinces, China, embedded with different subsoil strata were chosen to carry out the tamping test and relevant observations. In general, three categories of subsoil formations were encountered. For analytical consideration, A general profile of ground soil on a site in the south of Beijing is shown in Fig.2.1 for example.

![Fig.2.1 Soil logs compacted in Beijing](image)

2. Field Instrumentation and Observation

Observations were made in four major aspects:

(1) Tracing the moving behaviors of ground soil directly underneath the falling weight and that in the vicinity during tamping.

(2) Monitoring the movement of vibration of different depth and distances away from the tamping point indicating the intensity and...
attenuation of vibration of soil particles at certain points in order to:
(a) Verifying the effective depth of compaction.
(b) Determining number of tamping blows necessary for getting appropriate compaction.
(c) Determining spacing of compaction points for an appropriate covering over the whole area to be improved.
(3) Monitoring pore pressure evolution and dissipation as a guide to evaluating sequence and extent of consolidation of saturated soils to be compacted.
(4) As an environmental protection measure, observations were made on the existing structures under seismic induction.

In carrying out these observations, the following instrumentations were undertaken:
Markers were put in cross lines across the centre of tamping area corresponding to the falling weight (Fig.2.2) to show the horizontal and vertical movement of ground surface.

For obtaining a stereoview of the whole deformation of soil mass, we apply photogrammetric technique by using Universal Surveying Camera (UMK10/1318) in addition to direct measurement, taking successive snapshot, we got a series of pictures showing continuous deformation of ground surface round the print as shown graphically in Fig.2.3. It should be noted that different types of soil stratum gave different responses of deformation.

Meanwhile, vertical strips in white were put directly underneath to trace resultant movements in the elevations as shown in Fig.2.4.

For measuring vibration, acceleropickups were installed at definite intervals on the profile.

To verify the extent of liquefied soil layer caused by compaction and consolidation as a consequence of tamping, pore pressure variations were measured around the compaction point by means of piezometers and transducers.

III. ACTUAL BEHAVIOR OF GROUND SOIL UNDER DYNAMIC CONSOLIDATION

Dynamic consolidation is substantially a heavy impact exerted on the ground surface. Subsequently a very complicated series of wave responses will be excited in different manners as follows:
1. A series of compression-dilatational waves with a comparatively high velocity spread radially from the tamping point causing a push-pull displacement of the soil and resulting in an increase of pore pressure.
2. A series of shear wave with lower velocity but larger amplitude travel radially but causing soil particles shifted tangentially and as a result to form a closer and denser skeleton of the soil.
3. A series of surface Rayleigh wave with a distortional behavior spread out along the ground surface. Its transverse and longitudinal components with much larger amplitude and vertically backward moving trace of soil particles may cause surface materials to move up forming ground heaving within limited distance.

Based on the field observations, we have got close approximations to the real behaviors of soil under dynamic consolidations. These will be discussed in the following:
A. Displacement
Fig.3.1 shows the vertical displacement of ground soil underneath the tamping print.

Evidence shows that Rayleigh waves played an important part in the displacement versus depth. So far as the horizontal locus of the movement of soil particle is concerned, it appears to be a closed polygon showing soil
particle swaying to and fro in a period of about 7 blows of tamping as shown in Fig. 3.2.

\[ U(Z) = e^{-\frac{q}{N}} + e^{-\frac{q}{N}Z} \]  \hspace{1cm} (3.1)

\[ W(Z) = e^{-\frac{q}{N}Z} + e^{-\frac{q}{N}Z} \]  \hspace{1cm} (3.2)

where, \( N = \frac{2\pi}{L} \)  \( L \) wave length.

As it is the common case that \( a = 0.25-0.5 \), \( W(Z) \) with respect to the amplitude versus non-dimensional depth are shown in Fig. 3.3.

By both measuring actual displacements and calculating Rayleigh wave length with known Poisson's ratio, we got the real displacements curves which look like the theoretical ones as shown in Fig. 3.1 and 3.3. It can be noted that surface layer plays an important role in determining either the shape or the coordinates of these curves on the graph.

B. Acceleration

Acceleration means force for a specified mass in the sense of Newton's second law. So by measuring acceleration, we can evaluate the dynamic force attenuation with depth. Fortunately, we got the similar curves as that of the displacements. (Fig. 3.4)

Moreover, very interesting phenomenon is that the horizontal acceleration measured on ground surface at different place away from the tamping point has similar attenuation tendency (Fig. 3.5) as the vertical ones which has a logarithmic functional attenuation character. (3)

Generally it has the form as

\[ A_{max} = ax^{-b} \]  \hspace{1cm} (3.3)
where \(a=20\), \(b=1.46\), \(1.77\).

This means the maximum amplitude of acceleration varies inversely with horizontal distance by the rule of exponential functions.

C. Dynamic Pore Pressure Evolution and Dissipation

We concerned pore pressure changes in saturated low plastic soils under dynamic consolidation because it must be an evidence showing where consolidation occurs. Hence, it may be also an evidence showing the relation between the effect number of tamping blows and effectiveness (or degree) of consolidation.

As liquefaction is defined by dynamic triaxial test as the pore pressure approaches and equals to the confined pressure in the cell, we here-with define the liquefaction due dynamic consolidation in the ground soil as the dynamic pore pressure at a certain depth exceed the lateral pressure of the soil. It should be noted that thus defined liquefaction means the effective zone of dynamic consolidation can be expected. So we can make out the extent of soil effectively compacted by dynamic consolidation.

IV. CONSEQUENT ANALYSIS

Conclusions can be drawn from field work and apparent mechanism analysis in the following:

1. Determination of Effective Depth of Compaction

Menard in his early work gave the first approximation of the thickness of soil layer to be compacted as

\[Z<\sqrt{\frac{W}{M}H}\]  \hspace{0.5cm} (4.1)

where \(H\) is free fall distance.

This criteria is sometimes taken simply as

\[Z=\sqrt{\frac{W}{M}H}\]  \hspace{0.5cm} (4.2)

But by our experiences in Chinese engineering practice, including our field observations and instrumentations, associated with theoretical analysis, we found that \(Z\) must be much smaller for effective compaction.

By the law of conservation of energy, we know that the energy \(E\) of impact due to falling weight must be equal to the total energy density of the waved soil mass within the effective depth of compaction.

For the energy density, we assume the dynamic energy of a unit volume \((v_0)\) at a certain depth \((Z)\) in the soil is:

\[dE_t=\frac{1}{2}dm.v_i^2\]  \hspace{0.5cm} (4.3)

and \(dm=\rho dv_o\), where \(dm\) is the mass of that unit volume of soil. If wave is simple harmonic, then its shear velocity is

\[V_s=dA\cos \omega (t-\frac{Z}{V_s})/dt\]  \hspace{0.5cm} (4.4)

where \(A\) is the amplitude of the wave.

\[dE_t=\frac{1}{2}\rho dv_o A^2 \sin^2 \omega (t-\frac{Z}{V_s})\]  \hspace{0.5cm} (4.5)

This would be equal to the elastic potential energy due elastic deformation during vibration of the same unit. Thus

\[dE_s=dE_t\]  \hspace{0.5cm} (4.6)

The mean value of \(\sin^2 \omega (t-\frac{Z}{V_s})\) is \(1/2\). Then the total mean energy density will be

\[\Delta E=\frac{1}{2}\rho A^2 \omega^2\]  \hspace{0.5cm} (4.7)

By observing the whole volume of soil mass being compacted, the total mean energy may be assumed as an elliptical sphere with axes \(x, y, z\) which means the longer axis goes vertically. In case of plane axial symmetry and by the actual contour lines of equal displacement value (Fig.4.1),

we may take the approximation that \(x=y=1/2z\) and the total energy of the waving soil mass of an elliptical sphere within the effective depth will be

\[E_m=\frac{1}{2}\rho A^2 \omega^2 Z\]  \hspace{0.5cm} (4.8)

The total energy exerted by falling weight is

\[E_F=WH\]  \hspace{0.5cm} (4.9)

Thus equate equations 4.8 and 4.9 we get the real effective depth of compaction for a single impact of tamping to a homogeneous layer:

\[Z=\sqrt{\frac{6WH}{\pi \rho A^2 \omega^2}}\]  \hspace{0.5cm} (4.10)

In our cases, for instance, \(WH=200t-m\), sandy clay, \(\rho=0.179 t/\text{sec}^2/\text{m}^3\), \(A_{max} \approx 15\text{cm}\) (taking as an average of the pseudo-elastic deformation of the first four tampings in Fig.2.4), \(\omega=19.2/\text{sec}\), then by equation (4.10) we get
2. Induced Liquefaction and Its Extent in the Ground

Tamping induced liquefaction is the cause of dynamic consolidation of saturated soil. So, knowing the evolution of pore water pressure and making it in contrast to its lateral confining pressure, we can find out the volumetric extent of liquefaction which will reflect the effective scope of compaction.

By installing pore pressure transducers in different depth, we got the maximum dynamic pore pressure at each depth. So there is a critical elevation above which liquefaction occurs, but below which soil will remain its original state, hence less improvement can be seen with regard to dynamic consolidation.

From Fig. 3.6 we got the ground acceleration due to tamping versus its distance away from the compaction point. Their correlation is given by equation 3.3. Then, we know that liquefaction may occur on the ground surface some distance (X) away from that point where seismic force due to compaction must be greater than the shear resistance at the same point.

Fig. 4.3 gives pore pressure variations relating number of tamping blows at different levels inside and outside of the tamping print. It shows that peak values of pore pressure do exist and after the peak, soil tends to dilate. Hence thorough liquefaction towards denser state only takes place under limited number of tamping blows, say, three to five blows in our cases. This shall be discussed further in the following.

Fig. 4.4 gives the pore pressure ratio ($R_p$) at different points round the tamping print showing the scope of liquefactions due to dynamic consolidation can be specified with the boundary where $R_p = 1$. From this point of view, we may define the reasonable clearance between compaction points is about two times the width of the falling weight.

3. Effective Number of Blows of Tamping

Field practice of dynamic consolidation shows that number of blows of tamping is not necessarily proportional to the degree of compaction. Fig. 4.5 appears an optimum volumetric deformation of soils often occurring within five blows of tamping. Another evidence already shown in Fig. 4.3 that the maximum pore pressure exerted do not relate to the first blow of tamping but often occurs round the fourth blow. This may suggest for cohesive soils, particles may be compacted to a denser state gradually by rearranging their structure which takes only few times of tamping.

4. Environmental Effect

From civil engineering point of view, people, usually concern a great deal of the seismic effect on the existing structures nearby the dynamic consolidation point. This is also the major topic we are dealing with in this paper.

According to our experience in China and with the background of Chinese "Machine Foundation Design Code" (47), it is suggested to limit the
maximum acceleration $a_{\text{max}}$ excited on foundation due to hammering should be as follows:

- for foundation on loose sand $a_{\text{max}} < 0.1g$
- for foundation on cohesive soil $a_{\text{max}} = 0.2g$

Fig. 4.5 Volumetric deformations of soils shows optimum number of tamping blows often less than five

Referring to the acceleration attenuation along with distances away from the compaction point as shown in Fig. 3.5, we can define the safe minimum horizontal distance from the point of dynamic consolidation of $WH = 200t$-m should be no less than $17m$.

Alternatively, by examining the maximum displacement of particle vibration, we got similar rule as shown in Fig. 4.6. Referring to Richart et al. (5), we got a critical displacement for low frequency vibration (say $f$ is within tenths level) is about one tenth of an inch. Then the minimum distance of safety $x_s$ from the compaction point is as follows:

- for cohesive soil, $x_s > 25$ m ($A = 0.05mm$)
- for non-cohesive soil, $x_s > 30$ m ($A = 0.07mm$)

In case of very compact site in scope, dynamic tamping may result unavoidably influences on the adjacent structures, then isolation trench may help to diminish harmful vibrations. To verify this effect, we ran real observations on that site by digging trenches about two meters deep and less than one meter wide. It appeared that seismic responses on both sides of the trench differ with a clearly decreasing rate along with the distance from the compaction point as shown in Fig. 4.7. Thus we can draw conclusion that isolation trench is more effective in decreasing vibrational amplitudes to a considerable degree under dynamic consolidations.

V. CONCLUSIONS

For designing dynamic consolidation with an appropriate compaction effect, the following criteria are suggested with the background of the field work given in this paper.

1. Evaluation of effective depth of compaction can be modified analytically instead of pure empirical estimation. In applying equation (4.10), a trial of tamping for measuring $a_{\text{max}}$ is suggested when possible. This modification was verified and supported by a series of in-situ testings.

2. For saturated soils effective (minimum) spacing between compaction points is about two times the width of the falling weight. This may also be true with unsaturated soils.

3. The appropriate number of tamping blows is often limited and no more than five. More blows may be of no use and even harmful in our cases.

4. For environmental consideration of existing ground structures, a safe distance of no less than $17$ m (relating to acceleration response) or $25 \sim 30$ m (relating to displacement amplitude) is warranted. As a damping measure, isolation trench was proved to be more effective.

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