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SYNOPSIS In view of the fact that microscopic liquefaction can not be equated with the macroscopic one; further, owing to the unsolved difficulties in taking undisturbed samples of sand and in performing laboratory testing of liquefaction, the author has tried to search after new practical way to assess soil liquefaction potential by macroscopic approach. This paper presents a preliminary study which can coordinate each other with the laboratory microscopic procedures so as to make more reliable prediction to liquefaction potential and assessment of its seismic effect.

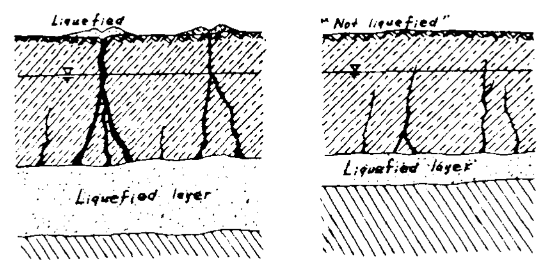
Earthquake induced soil liquefaction can be strictly defined by its mechanism in microscopic view point. (1) Nevertheless, definite concept on liquefaction mechanism can hardly be given when it is treated as a macroscopic damaging phenomenon. Practically speaking, judgement to soil liquefaction made so far according to the fact that whether there is any sand boils on level ground or any landslide on sloped ground. Despite such a definition is somewhat insufficient in mechanical sense, but it is very signigicant owing to the fact that only liquefaction with sandboiling can cause excess settlement or failure of ground. On the other hand, that without sandboils can never be found by people, therefore its damaging effect will be quite limited. From this view point, this article deals with the following research work with Xin Tai (1966), Liao Ning (Hai Cheng) (1975) and Tangshan (1976) earthquakes as background, in order to supplement laboratory studies.

1. MECHANISM OF SANDBOILING AND ITS EFFECT ON OVERLAIN LAYERS

1.1 Differences Between Liquefaction and Sandboiling

It should be noted that liquefaction and sandboiling are not of the same function and the latter is not necessarily the result of the former. Therefore it is not sufficient to explain sandboiling with the theory of liquefaction.

It was found in site investigation that the two layers shown in Fig.1.1 may have entirely different sequences. i.e. the thick liquefied layer in Fig.1.1 (A) may induce sandboiling whether the thin layer in Fig.1.1 (B) can hardly behave the same. Subsequently the latter might not be found to be liquefied by surface investigation. In other words, these two liquefied layers would be considered to have different seismic effects. Further, sandboiling takes place with liquefaction as a premise, other necessary conditions would be the effective overburden pressure and depth of ground water level. If the liquefied layer lies directly on ground surface, then no effective overburden pressure exists on its surface, and no sandboiling will take place.



(A) (B)

Fig.1.1 Fictitious difference of seismic effect on ground due to different water levels and different thickness of liquefied layers

1.2 Formation of Sandboils and Its Character

Fig.1.2 shows a cross section of a sandboil (A) or sand-vein (B) occurred in Tangshan earthquake. By inspecting the deposits in it (A), we can easily found that sandboiling took place and deposited at least twice in the same path before. The interface of the deposits represents the order of spurting and depositing.

As sandboil embodies, soil layer will be no more homogeneous or isotropic, and an easy way of drainage for porewater thus formed. Whenever a second event took place, sandboiling would come along with the pre-existing sandboils and sand-veins. Consequently, as a general rule, once there happens sandboiling in a strong earthquake, there will be the same thing in a later event of even lower intensity.

Fig.1.2 (A) (B)

Fig.1.3 shows a sandboil having "boiled" successively throughout the main shock and aftershock of Tangshan earthquake (July 28, 1976). The material around the "sand Volcano" ever carried out and deposited by water spurting, so the later the material deposited the finer the particles will become. There did exist some sandboils which lasted spurting water and sand particles right after each shock for about one year duration. This is what we called the reoccurrence of sand boiling.

Fig.1.3

1.3 Possible Influence of Sandboiling on Overlain Soil Layer

In the whole process of liquefaction up to sandboiling, the liquefied layers undergo two different stages of being densified and loosened.

It has been widely accepted that the premise of liquefaction is densification of sand and this will result in the increase of pore pressure. But as sandboiling begins to occur, the overlain soils and liquefied layer itself will be acted by uplift pressure which is transferred from dynamic pore pressure due to sandboiling, thus their density will be decrease. Fig.1.5 shows a density variation in terms of blow counts of SPT and correlated relative density before and after Tangshan event (1976). The method and facilities were all the same for each test.

Fig.1.4 shows the corresponding variation in cone resistance q_c calculated as the arithmetic mean of test data. From a single cone penetration hole, we can observe the following rules (Fig.1.6):

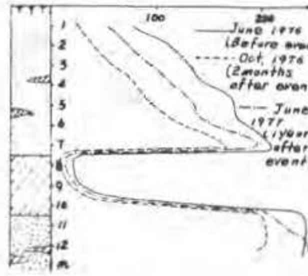


Fig. 1.4

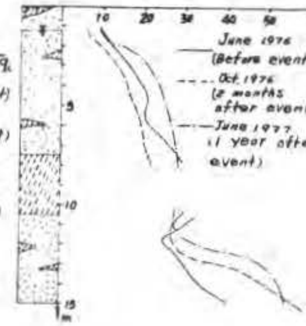


Fig. 1.5

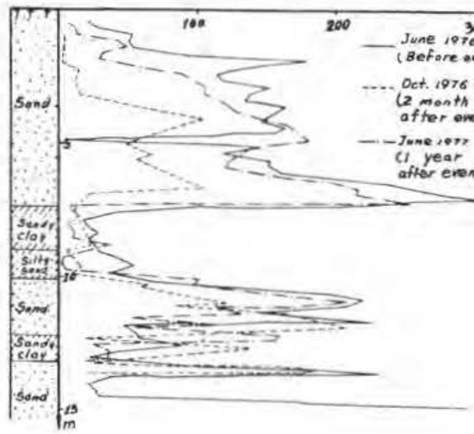


Fig.1.6

(1) Right from the main shock, overlain soil layers began to be loosened.

(2) About one year later, the loosened layers seemed to recover their original densities. But the deeper layer is much quicker to approach to its end due to larger overburden pressure.

(3) The third layer in Fig.1.5 being fine sand and silty sand had obscure variation in density. It would be considered the very liquefied layer and sandboiling would be only within this stratum.

The above mentioned behaviors could be interpreted by Fig.1.7, where a single liquefied layer is supposed up to ground level. Whether it will become denser or looser after an event would mainly depend upon the contrast between effective overburden pressure, dynamic pore pressure and earthquake acceleration. Consequently, by arithmetic summation, we may get a neutral point at a certain depth acting as the critical point between the loosening and densifying.

2. COUPLED FORCES DURING LIQUEFYING PROCESS

A strange phenomenon was observed in macroscopic research: on the same level ground, intensified sandboiling occurred within the floor of certain building, whereas on the uncovered free ground only slight sandboiling existed. This was true for both nearfield or farfield. This phenomenon means that the existence of building does not even increase the effective overburden pressure, and will contrarily intensify sandboiling. The original pore pressure that caused liquefaction ever before is no longer associated with lasting sandboiling. And the coupling of forces act upon the liquefied layer when it becomes a liquid medium.

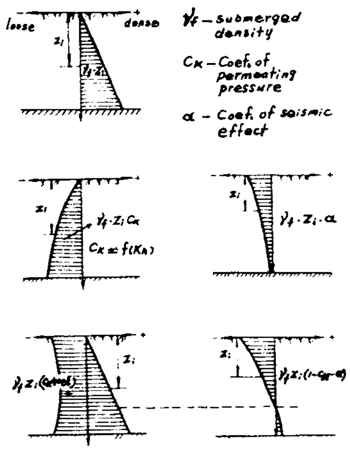


Fig. 1.7

A single storey industrial building with basement situated 30 km away from the epicenter in Tangshan earthquake is shown in Fig.2.1 The floor is plain concrete slab 15 cm thick which was broken longitudinally by very strong spurting of sand and water. But liquefaction in free ground just outside of the building is relatively slight. By tentative interpretation of this phenomenon, the following factors may be the forces coupled in this performance:

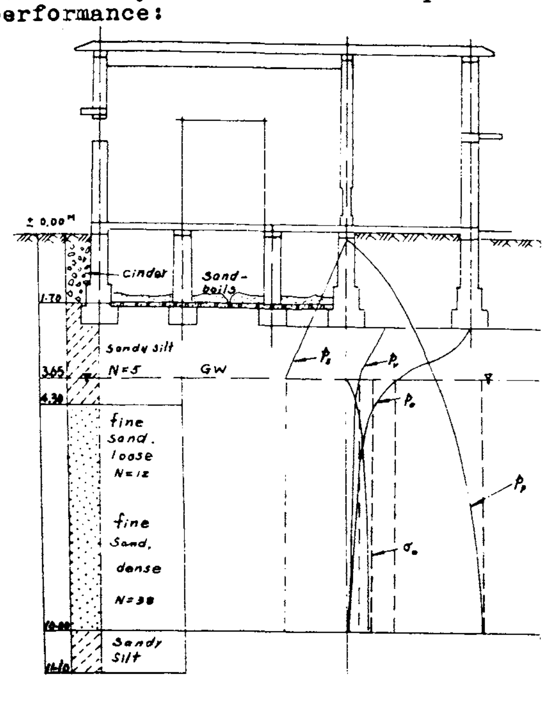


Fig.2.1

(1) Dynamic pore water pressure (σ_o)

This is the seismic force acting on free water in the voids and pushing the pore water out to transfer stresses. When the liquefied layer (with thickness h) is quite permeable, time duration of earthquake shaking is relatively long, and depth of ground water is shallow, we can use Westguard's formula to estimate this force at certain depth (y), namely,

$$\sigma_o = \frac{7}{8} K_h \cdot \gamma_w \cdot \sqrt{hy}$$

where K_h is the horizontal seismic coefficient $(=\alpha_h/g)$, γ is the density of water.

(2) Pressure due to P-wave (p_p)

In a long time duration of ground motion the forces exerted from P-wave will be transferred to liquefied layer and tends to squeeze its materials out. The maximum value may be calculated from the following equations. (2)

$$p_p = \rho \cdot V_p \cdot \omega \cdot D_o \frac{1}{1+\alpha} \sqrt{2(1+\alpha^2) + 2(1-\alpha^2)\cos\frac{4\pi z}{V_p T}}$$

where $D_o = \alpha_p T^2/4\pi^2$

D — the total displacement of surface wave,
ω, V_p, α_p — frequency, wave velocity and acceleration in the liquefied layer.
α — impedence ratio of wave
where D_{max} will occur at Z = 0 (ground surface) and $p_{p\,max}$ at $Z = V_p T/4$

(3) Vertical shaking force (p_v) or additional dynamic force by footing during earthquake.

This is substantially the mass of building acted by seismic acceleration of the designed intensity. This force will be transferred also to the liquefied layer when it becomes a liquid medium. Thus

$$p_v = K_v \, p_o$$

where K_v is the vertical seismic coefficient $(K_v = \alpha_v/g)$, p_o is the additional load applied by the building. During liquefying, the liquefied layer bears the load of the building all the time. By Pascal's law, this load will be transferred to any point in any direction of the liquefied layer and acts as dynamic loading due to ground motion. So the total load would be $\Sigma p_v = p_o(1+K_v)$

(4) Over burden pressure of soil on liquefied layer

This pressure (p_s) acts on the top of the liquefied layer and would be transferred to the entire thickness to couple with other forces. When the saturated sand layer approaches to being thoroughly liquefied, the above mentioned forces will couple together in the liquid medium, forming an overwhelming tendency to spurt sand and water out of it.

Given relevant data as:

$$V = 260\ m/sec\ ,\quad \gamma = 0.0018\ Kg/cm^3$$
$$p_o = 15\ T/m^2\ ,\quad K_h = 0.5\ ,\quad \alpha \approx 1.0\ ,\quad f \approx 3H_z$$

then the coupled forces would be

$$\sum p = \sigma_o + p_e + \sum p_v + p_s \approx 26\ T/m^2$$

that is enough for crushing the concrete slab of the indoor floor. So far as our study is concerned, this case would be of practical significance for lighter buildings with footing directly on (or adjacent to) the top of the liquefied layer.

3 THE MACROSCOPIC FEATURES OF SOIL LIQUEFACTION

People used to verify soil liquefaction on level ground by inspecting whether sandboiling took place or not during a stronger earthquake. This would be a commonly accepted criteria for identifying liquefaction of a site. However, when we lift our sight high enough beyond the ground surface, we will find that within a larger area, say several sq. km. or even ten's of km^2, sandboils as a whole will form a macroscopic pattern of different mechanism. Their features will vary with topographic, geomorphological and structural conditions and have quite different effect on ground damage.

3.1 The Macroscopic Distribution of Liquefaction

Fig.3.2 is the liquefied area with sandboils along the Dou River in Tangshan urban district, and Fig.3.1 is that along Hai River in Tienjing urban area. Both of them happened immediately after Tangshan earthquake. These figures have revealed some regularities:

(1) On basically level ground, sandboiling is obvious on the convex bank of a river, whereas on the conceve bank nothing in particular, even no sandboil at all.

(2) On both sides of a straight river course or on the site far from the river, sandboiling is apparently weakened, even invisible.

(3) On the site surrounded by several river bends (skirt of river bends), macroscopic liquefaction tends to be more severe and more complicated in figure.

3.2 Macroscopic Patterns of Liquefaction

The distribution of sandboils represents the topographical, geomorphological and structural factors having effect on liquefaction. In analyzing such effect, we have come to three kinds of fundamental patterns of macroscopic liquefaction by the aid of air-photo interpretation. (3)

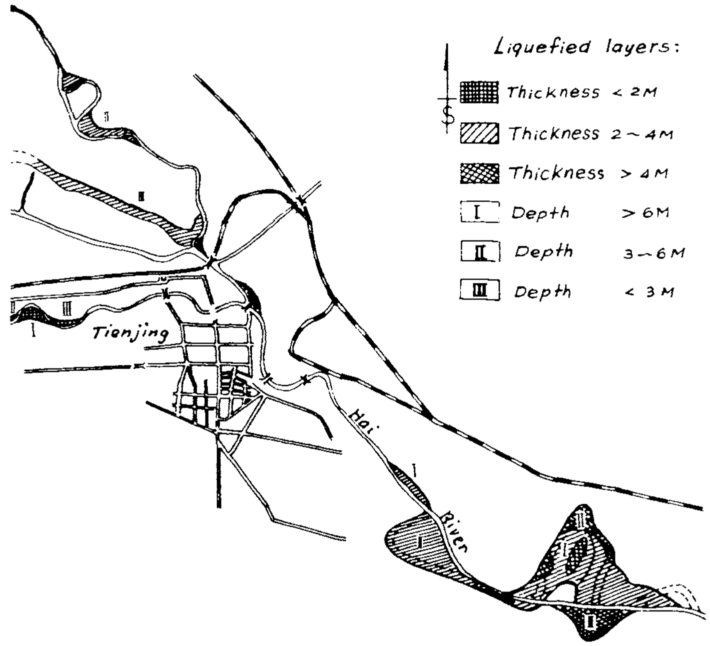


Fig.3.1

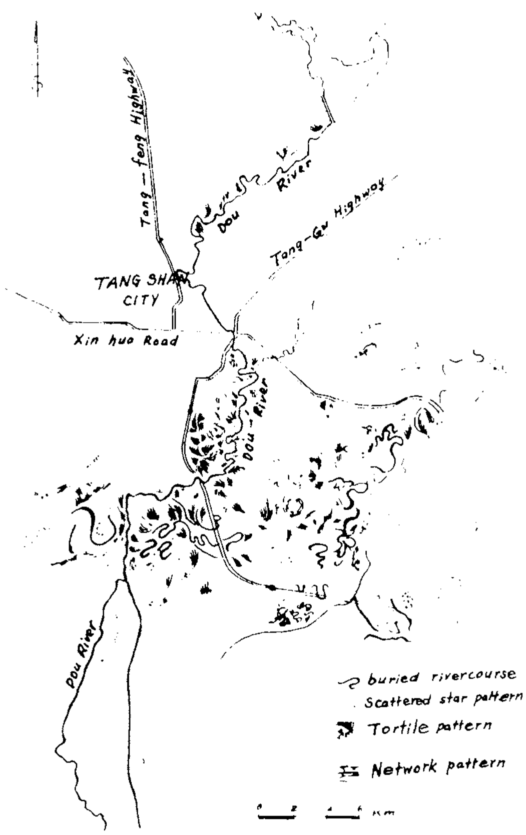


Fig.3.2

(1) Scattered stars pattern

This is a basic one which is formed by homogeneously scattered sandboils. It often exists on the site where underlying soil layers are mainly homogeneous and nothing particular in topographic and geomorphological sense. In such case, the pressurized pore water percolates freely with equal spacing as shown in Fig.3.3

Fig.3.3

Fig.3.4 (Note: part of network of sandboils were shaded by tall corps in the darkened area)

(2) Network Pattern

Fig.3.4 is a real example for network pattern of sandboils. It took place often on the convex bank of a river bend, and in the central area of the bend with special orientation, i.e. parallel to the axis of quasi-parabolic river bend, and with equal spacing. Surface ruptures are in tension. Fig.3.5 presents a damaged single storey hospital. It should be noted that there were 5 single storey houses constructed all the same but not of the same fate in earthquake.

Fig.3.5 Houses damaged intermittently: (1),(3) stood still; (2),(4),(5) crushed down

During the Tangshan event, they behaved intermittently different, i.e. five houses either crushed out or stood still every other row. And each row coincides with the network pattern of sandboils. By the author's research, this is formed due to stationary waves propagating normally to the symmetric axis of the river bend. The general equation for stationary wave is

$$u(x,t) = X(x)\,T(t)$$

and $$X(x) = \sin\frac{n\pi x}{L}$$

$$T(t) = A\sin\frac{n\pi a}{L} + B\cos\frac{n\pi a}{L}$$

Thus $$U_n(x,t) = \sin\frac{n\pi x}{L}\cdot\left(A\sin\frac{n\pi a}{L} + B\cos\frac{n\pi a}{L}\right)$$

For each value of n, there is a corresponding stationary wave; L may be considered to be the distance between two sides of the river bends, "a" equals to half wave length ($a = 2fL/n$).

(3) Tortile Pattern

It is shown clearly in Fig.3.6 that sandboils in the skirt of river-bends form one or several tortile figures. On one site, tortile patterns often rotate in the same direction. At the center or axis of rotation, sandboiling tends to diminish. Besides, in area of embedded or transferred riverbed, same pattern will encounter.

Fig.3.6

This pattern might be produced by two factors:

(1) Wave-fronts reflected from different river-bends intersect together at a certain place resulting in intensified torsional movement of ground.

(2) Inclined interfaces of the liquefied layer and its overlying stratum may cause torsional movement during the transferring of input seismic waves. Let us assume a vector field of a wave-front in a relatively rigid medium to be $\alpha(x,y,z)$, then its variation increment $\Delta\alpha$ can be expressed in three dimensional matrix

$$\Delta\alpha=\begin{bmatrix} \frac{\partial\alpha_x}{\partial x} & \frac{\partial\alpha_y}{\partial y} & \frac{\partial\alpha_z}{\partial z} \\ \frac{\partial\alpha_y}{\partial x} & \frac{\partial\alpha_z}{\partial y} & \frac{\partial\alpha_x}{\partial z} \\ \frac{\partial\alpha_z}{\partial x} & \frac{\partial\alpha_x}{\partial y} & \frac{\partial\alpha_y}{\partial z} \end{bmatrix}$$

Let i,j,k be the basic vectors and ∇ be the Hamilton operator, then the rotation of the field will be

$$rot\alpha=\nabla\alpha=\begin{bmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ \alpha_x & \alpha_y & \alpha_z \end{bmatrix}$$

If horizontal rotation occur, then by definition, we have

$$\alpha=\omega^2 r=\begin{bmatrix} i & j & k \\ 0 & 0 & \omega^2 \\ x & y & z \end{bmatrix}$$

$$\therefore \alpha_x=-\omega^2 y, \qquad \alpha_y=\omega^2 x$$

namely, $rot\alpha=-i\omega^2\frac{\partial x}{\partial z}-j\omega^2\frac{\partial y}{\partial z}+k\omega^2\neq 0$

Thus, torsional moment makes confirmation to the assumption where tortile features do exist.

Different patterns have different effect on ground damage. The "scattered star" pattern has lighter damaging effect; the "network" pattern has an alternatively damaging effect with equal spacing on ground of about half length of surface S-wave; the "tortile" pattern may be the most destructive one due to its torsional action other than normal shaking.

By studying the geological and topographical conditions which produce various patterns of macroscopic liquefaction, it is most likely making predictions to the damaging effect and manner of a site in future events.

4. ASSESSMENT OF LIQUEFACTION

In engineering practice, two questions should be answered: (1) How about the liquefaction potential of a site ? (2) How about its damaging effect which can really be predicted?

4.1 Macroscopic Liquefaction Potential

In this assessment two promises should be made: (1) Field intensity of a site in future event will not exceed the largest historical one. (2) Sandboiling will reoccur at the same place as it was. From the author's viewpoint these will come true in future events.

In North China, several strong earthquakes ever induced sandboiling each time at the same place. For instance, on the site of Wool String Factory of Tienjing, there were sand-boils always keeping active so far even for those event of lower intensity (I=5 M.M. scale) on that site.

On the other hand, we did ever excavate old sandboils and sand veins encounted in the old tectonic rupture zone. They are no more active and pre-historical evidence is clear. (Fig.4.1) Its enlightment is that old liquefaction and sandboils were often associated with old tectonic soil ruptures. Based on this fact and above premises, we may simply perform necessary explorations and inspect sandboil, sandveins and tectonic ruptures in soil if any. By this means and associating with the laboratory study, we can make more effective prediction on liquefaction potential and the seismic effect thereof.

Fig.4.1

4.2 Macroscopic Damaging Effect of Liquefaction

So far as microscopic study is concerned, liquefaction has ever been considered as only a disastrous factor to foundation failure. Nevertheless, macroscopic study will prove that liquefaction may save ground structures from a really overwhelming disaster. In Tangshan earthquake, a farmer's house settled down in the seriously liquefied area, where ground cracked out due to severe shaking, Fig.4.2(A); large sandboils almost buried the house. Meanwhile, ground failure tilted the house, where a man were standing in the "sand volcano". Fig.4.2(B) It was really terrible for a look.

Fig.4.2 (A)

Fig.4.2 (B)

However, it was actually lucky that no body in the house injured, not even killed. And houses stood still as it had been, although some damages could be seen at eaves and corners.

Therefore, as a sequel of liquefaction, foundation failure on level ground would apparently protect houses and peoples in it from a disastrous event by means of the impedence of the liquefied layer to seismic waves. This positive action should not be neglected.

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