Analysis of ramming settlement based on dissipative principle

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Abstract. The deformation of soil is a kind of dissipative structure under the action of dynamic compaction. The macroscopic performance of soil to steady state evolution is the change of ramming settlement in the process of dynamic compaction. Based on the existing solution of dynamic compaction boundary problem, calculated ramming effectiveness (W) and ramming efficiency coefficient (η). For the same soil, ramming efficiency coefficient is related to ramming factor λ=M/ρv. By using the dissipative principle to analyze the law between ramming settlements and ramming times under different ramming energy and soil density, come to the conclusion that: Firstly, with the increase of ramming numbers, ramming settlement tends to a stable value, ramming effectiveness coefficient tends to a stable value. Secondly, under the condition of the same single ramming energy, the soil density of before ramming has effect on ramming effectiveness of previous ramming, almost no effect on ramming effectiveness of subsequent ramming. Thirdly, under the condition of the same soil density, different ramming energy correspond to different steady-state, the cumulative ramming settlement and steady-state increase with ramming energy.

1. Introduction

Dissipative theory, a study of the open system away from equilibrium states, by constantly exchanging energy and material with the outside world, from the original disorder state to the orderly state of evolution. It proposes that the non-equilibrium state is the source of order, and the nonlinear function is the ordered power [1]. It has broken away from the thinking of classical theory, had achieved fruitful results in the study of petrology, physics, architecture and so on [2,3,4,5]. For dynamic compaction, the open, unbalanced, nonlinearity is absolute, the closure, balance, and linearity is relative. With the creation of dissipative theory and nonlinear dynamics, It is possible to apply new thinking to consider the problem in the dynamic compaction.

In the reinforcement effect of dynamic compaction, many scholars have used various methods to research. For example: S. L Lee etc [6] set up the empirical equation about average ramming volume, ramming energy and Soil condition, By organizing the field data. Takada [7,8] thinks ramming volume is proportional to the momentum of the hammer and the square root of ramming times, is inversely proportional to the area of hammer, by conducting data of dynamic compaction model and field test. Zhirong Niu etc [9] get the method of settlement calculation, by analyzing numerically vibration characteristics of soil, assuming that soil for quasi elastic. Chun Liu etc [10] derive the special solution equation for the ultra-static pore pressure and the wave equation for saturated soil, Through using wave theory to study the instantaneous process of dynamic compaction. Mincai Jia etc [11] study the dynamic response of sandy soil foundation, through using similarity theory to Set up granular flow.
model of sandy soil, it's the first time to reveal the dynamic response characteristics of sandy soil from the perspective of view. From the current research status, The research is based on regional empirical data and empirical accumulation in the reinforcement effect of dynamic compaction, the applicability of calculation method and relationship by numerical simulation are narrow, also with respect to the change of ramming and energy transfer have not been solved well.

So in view of the existing problems, based on the existing solutions of dynamic boundary problem [12], calculate the formula of ramming effectiveness coefficient for gravel filling foundation. By using engineering data, build the changing curves of ramming settlements along with ramming times under the different combinations of ramming energy and soil density, reveal the variation rule of ramming settlements, Also analyze the dissipation process of ramming energy along with ramming settlement through using dissipative theory.

2. Research methods and data collection

2.1. Energy dissipation of dynamic compaction process
Engineering site soil is exchange of matter, energy, and information with the outside in the evolution process of deformation and destruction, So foundation soil is an open system [1]. The foundation soil is loose, the particles are not close enough and the void ratio is larger before dynamic compaction, It's in a non-equilibrium state. When outside conditions change, the deformation of soil is more random, this system is unstable.

With continuous ramming action, the energy of soil, density and ramming hole depth get larger and larger, the void ratio get smaller and smaller, From the non-equilibrium thermodynamics, the supply of these energies is maintained through the energy dissipation of the system and the non-current dynamics. In the deformation process of foundation soil, Mechanisms of energy dissipation and nonlinear dynamics are provided by the irreversible change process like that the change of shape and position of soil particles, plastic hardening, heat conduction, chemical reaction. Thus, the foundation soil of dynamic compaction is a dissipative structure.

The purpose of dynamic compaction is to bring the soil from disorder to order, absorption negative entropy flow, reduced positive entropy flow. The process of dynamic compaction is to continuously input negative entropy flow into the system, to continuously suppress internal entropy of the system. Make the total entropy of soil system in a low state, the void ratio is smaller and smaller, the density is larger and larger, the randomness of relative displacement between soil particles decrease, thus, the soil is developed in an orderly and stable state, which is the purpose of strengthening the soil. On the premise that the ramming energy can remain constant, with the increasing of ramming number, the system gradually developed to a stable and orderly state, at the same time, the energy of system needed to improve the stability and ordered state gradually decreases. Namely the efficiency coefficient of ramming is gradually reduced, the impact of subsequent ramming on the reinforcement effect is gradually reduced, in the end, tending to a stable state, the ramming efficiency tends to a certain stable number, at this point, the foundation soil has been compacted, the remaining energy will dissipate in the form of a vibrating wave. the stable state is determined by ramming energy.

2.2. The calculation of dissipation energy in the process of dynamic compaction
For the total work done in the dynamic compaction, some of the energy is dissipated, except for the soil's damping and rebound consumption . When the system evolves into a steady state, the dissipation of energy is consumed to maintain steady state. The macroscopic performance of soil to steady state evolution in the dynamic compaction process is the change of ramming settlement.

The macroscopic performance of the soil to the new stable state is that the ramming settlement tends to a certain stable value. So in the process of dynamic compaction ,the dissipation energy is equal to the total work done by the impact loading(W1) minus the damping and rebound energy of the soil(W2), Defining the dissipation energy in the process of dynamic compaction as ramming
effectiveness, So the ramming effectiveness \( W = W_i - W_f \), the coefficient of ramming effectiveness \( \eta = (W_f - W_i)/W_i \), the derivation process is as follows:

Jiahuan Qian etc [14] used the theory of structural dynamics to deduce the curve of stress and displacement over time of dynamic loading and unloading process.

\[
\sigma = \frac{\sqrt{MS}}{m_c} \sin \left( \frac{M}{S} t \right), \quad W = \frac{\sqrt{M}}{S} \sin \left( \frac{S}{M} t \right)
\]

Loading stage: \( t_0 = \frac{\pi}{2} \sqrt{\frac{S}{M}} \)

Unloading stage: \( w = \frac{\sqrt{M}}{S} \left[ 1 - \frac{S}{S'} \right] \left( \cos \alpha' - \frac{R'}{\sqrt{4MS - R'^2}} \sin \alpha' \right) \)

Unloading duration: \( t_{ul} = \frac{1}{\omega_0} \arctan \frac{4MS}{R'^2 - 1} \)

Residual subsidence: \( w_i = \frac{\sqrt{M}}{S} \left( 1 - \frac{S}{S'} \right) \)

The total duration: \( T = \frac{\pi}{2} \sqrt{\frac{S}{M}} + \arctan \frac{4MS}{R'^2 - 1} \)

In the formula: \( \nu \) --The speed at which the ramming hammer hits the ground, \( \nu = \sqrt{2gh} \); \( \omega_0 \)--the radius of ramming hammer; \( M \)--the quality of ramming hammer; \( S \)--Loading elastic constant , \( S = \frac{2\nu E}{1 - \nu^2} \); \( S' \)--Unloading elastic constant, \( S' = \frac{2\nu E_{ull}}{1 - \nu^2} \) [15] ; \( R' \)--viscosity coefficient of unloading foundation , \( R' = 0.6\pi_0^2 \frac{\rho E_{ull}}{1 - \nu^2} \), \( \rho \) -- soil density.

Regardless of the influence of energy dissipation and damping in air, so the loading stage does work \( W_i = \frac{1}{2} M \nu^2 \). Consider the influence of damping and rebound of soil. so the unloading stage does work \( W_f = \int_0^1 \pi_0^2 \sigma(t') \omega(t') dt' \). Plug in \( \eta = (W_1 - W_2)/W_1 \)

Define the ramming factor: \( \lambda = M / \rho_0 \cdot \nu \)

So the coefficient of ramming effectiveness is correlation with \( \nu \), \( \lambda \), and \( E / E_{ull} \).

For the saturated viscous soil, \( E / E_{ull} = 1 / 1.6, e^{\frac{\nu}{M}} = 1 / 2, \nu = 0.4 \) so

\( \eta = 1 - \frac{\lambda}{\lambda - 0.8} \left( 0.31 + \frac{0.5}{\lambda} \right), \lambda \rightarrow \infty, \eta \rightarrow 69\% \)

(2)

For the gravel filling soil, accordingly, to the literatures[16,17,18], \( E / E_{ull} = 1 / 4, e^{\frac{\nu}{M}} = 1 / 2, \nu = 0.3 \) so

\( \eta = 1 - \frac{\lambda}{4\lambda - 2.2} \left( 0.5 + \frac{0.5}{\lambda} \right), \lambda \rightarrow \infty, \eta \rightarrow 87.5\% \)

(3)

According to the formula(2) and (3), \( \eta \) is positively correlated with \( \lambda \), According to the formula(1), \( \lambda \) is negatively correlated with \( \rho \) . So \( \eta \) is negatively correlated with \( \rho \), and is positively correlated with \( M \).

2.3. Site conditions and data acquisition

The terrain of the construction area has a large relief, and the general southeast to northwest slopes. Backfill the field with gravel soil before dynamic compaction construction. The thickness is 3-8m. hammer no.1 weight 20t, rammer diametre is 2.2m; hammer no.2 weight 10t, rammer diametre is 2m; in the 1st test area, firstly the hammer no.1 with 2 times of points ramming under the height of 10m, the distance of the ramming points is 5m by 5m, and then the hammer no.2 with full ramming under
the height of 10m. in the 2nd test area, firstly the hammer no.1 with 2 times of points ramming under the height of 12.5, 7.5 and 5m, the distance of the ramming points is 5m by 5m, and then the hammer no.2 with full ramming under the height of 10m. Strictly follow the relevant specifications [19] and the manual [20] during construction, accurately measure and record the ramming settlement.

After ramming, in the 1st test area, selected three data of ramming settlement and numbered 1-1, 1-2, 1-3. And the same as the 2nd test area, Also numbered 2-1, 2-2, 2-3.

3. The results and analysis

3.1. Analysis of ramming settlement under the condition of the same single ramming energy

3.1.1. Under the condition of the same single ramming energy and soil density. According to the investigation and geotechnical tests, 1-1 ramming point’s backfill soil thickness, soil density, selecting hammer, height of lift are same with 1-2 in the 1st test area. So the changing laws of ramming settlement along with ramming times are shown in Fig.1.

![Fig.1 The changing laws of ramming settlement along with ramming times](image)

Fig.1 shows, the curves of single ramming settlement and cumulative ramming settlement of 1-1 ramming point are coincident with 1-2.

According to the formula (1), \( \eta \) is correlated with \( M \), \( \rho \) and \( r_0 \), also according to the investigation and geotechnical test before ramming, the soil density of 1-1 is the same with 1-2, both of hammers are 20t. So under the same ramming times, both of \( \eta \) and single ramming settlement are same, So get the single ramming settlement and cumulative ramming settlement of 1-1 ramming point are coincident with 1-2.

Fig.1 show, as the increase of ramming times, the single ramming settlement gradually decreases, but the rate of decrease is slowing down. As the increase of ramming times, the cumulative ramming settlement gradually increases, but the rate of increase is slowing down. At last the cumulative ramming settlement tends to a stable settlement.

Under the condition of the same single ramming energy, as the increase of ramming times, the porosity of soil gradually decreases. At last, it tends to the limiting porosity [21], the soil density tends to a certain stable value, the coefficient of ramming effectiveness (\( \eta \)) tends to a certain stable value, the single ramming settlement tends to a certain smaller settlement, the cumulative ramming settlement tends to a certain stable settlement.
As the increase of ramming times, the effect of saturation is increasing[22], the evolutionary efficiency of the system gradually decreases, the system tends to a stable state, So the rate of decrease of single ramming settlement and cumulative ramming settlement are slowing down.

3.1.2. Under the condition of the same single ramming energy and the different soil density. According to the investigation and geotechnical tests, In the 1st test area, 1-1 ramming point’s Backfill soil thickness, selecting hammer, height of lift are same with 1-3, but 1-1 ramming point’s soil density is smaller than 1-3. So the changing laws of ramming settlement along with ramming times are shown in Fig.2.

![Fig.2 The changing laws of ramming settlement along with ramming times](image)

Fig.2 shows, the cumulative ramming settlement of 1-1 is larger than 1-3.

The soil porosity of 1-3 is smaller than 1-1, but the soil density of 1-3 is larger than 1-1, The initial stable state of 1-3 is above 1-1, and because of the same ramming energy correspond to the same final stable state, so 1-1 ramming point requires more energy than 1-3 when they evolve to a higher stable state. However, the macroscopic performance of soil to steady state evolution is the change of ramming settlement, so the cumulative ramming settlement of 1-1 is larger than 1-3.

Fig.2 show, when the first three ramming, the single ramming settlement of 1-1 is clearly larger than 1-3, but the subsequent single ramming settlement is basically the same.

Before ramming, the soil density of 1-1 is smaller than 1-3. According to the formula(3), when the previous several ramming, the coefficient of ramming effectiveness (η) of 1-1 is larger than 1-3, also both of ramming energy is the same, so ramming effectiveness(w) of 1-1 is larger than 1-3, so the single ramming settlement of 1-1 is clearly larger than 1-3 when the first three ramming. Along with the increasing of ramming times, the effect of saturation is increasing, the evolutionary efficiency of the system gradually decreases, the rate of decrease of coefficient of ramming effectiveness (η) is slowing down, at last tends to a stable value. So the subsequent single ramming settlement is basically the same.

3.2. Analysis of ramming settlement under the condition of different single ramming energy

Choose three ramming points and numbered 2-1,2-2,2-3 in the 2nd test area. According to the investigation and geotechnical tests, among of backfill soil thickness, soil density and hammer are the same, but the lifting height of 2-1 is 12.5m, the lifting height of 2-2 is 7.5m, the lifting height of 2-3 is 5m. So the changing laws of ramming settlement along with ramming times are shown in Fig.3.
Fig. 3 shows, under the same soil condition, the larger the ramming energy is, the larger the cumulative ramming settlement is.

Different ramming energy corresponds to different stable state. The larger the ramming energy is, the higher the stable state is. Also 2-1, 2-2 and 2-3 have the same soil density and backfill soil thickness, get that the soil states of ramming points are basically the same. However, the macroscopic performance of soil to steady state evolution is the change of ramming settlement. So get that the higher the stable state is, the larger the cumulative ramming settlement is.

Fig. 3 show, under those three kinds of ramming energies, the first few single ramming settlements have obvious difference, but the subsequent is basically the same.

According to the formula (1), $\eta$ is correlated with $M$, $\rho$ and $r_0$. $\eta$ is uncorrelated with the lifting height. And according to the formula (3), $\eta$ is positively correlated with $\lambda$. So the first few single ramming times the coefficient of ramming effectiveness ($\eta$) of 2-1,2-2 and 2-3 are the same. So the larger the ramming energy is, the larger the ramming effectiveness is, and the larger the single ramming settlement is. Along with the increasing of ramming times, the effect of saturation is increasing, the evolutionary efficiency of the system gradually decreases, the coefficient of ramming effectiveness gradually decreases, at last it tends to a stable value. So the subsequent single ramming settlements are basically the same.

4. Conclusion and outlook

4.1. conclusion

Through calculation and analysis, get the following main conclusions.

The deformation of soil is a kind of dissipative structure under the action of dynamic compaction. The macroscopic performance of soil to steady state evolution is the change of ramming settlement in the process of dynamic compaction, the macroscopic performance of soil to a new steady state is ramming settlement is close to a certain stable value.

The ramming effectiveness $W = W_1 - W_c$, the coefficient of ramming effectiveness $\eta = (W_1 - W_c) / W_c$, for the gravel filling soil $\lambda \to \infty$, $\eta \to 87.5\%$.

Under the condition of the same single ramming energy, along with the increase of ramming times, the porosity of soil gradually decreases, at last, it tends to the limiting porosity, the soil density tends to a certain stable value, the coefficient of ramming effectiveness ($\eta$) tends to a certain stable value,
the single ramming effectiveness ($w$) tends to a certain stable value, the single ramming settlement tends to a certain smaller settlement, the cumulative ramming settlement tends to a certain stable settlement.

Under the condition of the same single ramming energy. In the first few single ramming times, the smaller the soil density is, the larger the coefficient of ramming effectiveness ($\eta$) is, the larger the single ramming settlement is. Along with the increasing of ramming times, the effect of saturation is increasing, the evolutionary efficiency of the system gradually decreases, the rate of decrease of coefficient of ramming effectiveness ($\eta$) is slowing down, at last tends to a stable value. So the subsequent single ramming settlement is basically the same.

Under the condition of the same soil conditions and density, different ramming energy corresponds to different stable state, the larger the ramming energy is, the higher the stable state is and the larger the cumulative ramming settlement is.

4.2. Existing problems and outlook
This paper uses the dissipative principle to analyze the law between ramming settlements and ramming times under different combinations of ramming energy and soil density. But it just makes some qualitative discussions, failure to propose more precise theoretical solutions. Further research is needed to guide engineering practice.

Further research can be made in the following aspects.

- Use engineering experience and the relationship of $\eta$ and $\lambda$ to calculate the compactness of soil after ramming.
- Use dynamic load test principle to get the change of foundation bearing capacity in the process of ramming.
- Build a dissipative potential model to study the energy dissipation in the process of ramming.

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