Experiment and Simulation of Explosive Compaction in Loess with #2 Rock Emulsion Explosive

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Abstract. To overcome the difficulty of field experiment of explosive compaction (EC) technology for strengthening embankment of existing highway and to verify the reliability of numerical simulation, this paper took strengthening loess embankment of a highway with #2 rock emulsion explosive as an engineering background and put forward the method of combining small-scaled experiment with numerical simulation. While carrying out the experiment of EC, a finite element model of explosion in soil was built with soil parameters obtained from geotechnical experiments and other parameters. Then, ANSYS/LS-DYNA was used to proceed numerical simulation. Finally, the simulation results were compared with the results obtained by small-scaled experiment to verify the correctness of the model, material parameters and the simulation method. This paper not only verifies and ensures the reliability of numerical simulation, but also avoids the risk of field experiments on existing highway. It provides basis for taking parameters, modeling, and simulating according to the actual size of the loess embankment of existing highway to be strengthened.

Introduction

In recent years, loess is widely used in highway construction in China, but the collapsible property of loess is the main factor that causes the settlement of embankment. During two years after the opening of a highway in Hebei Province in 2010, its cumulative settlement significantly exceeded the national standards that the cumulative post-construction settlement of asphalt pavement on general section of highway developing during 15 years must be limited in 30cm [1]. With information from geological radar, surface wave detector and drilling samples, it was found that the embankment was built up with collapsible loess. When loess absorbs water, its structure will be destroyed and serious settlement will occur under the combined action of its gravity and the upper load.

Common methods used to reinforce embankment include grouting and compaction piles. Obviously, grouting is not suitable for wet collapsible loess. Most of compaction piles require predrilled wide holes with diameters from 30 to70cm. And for almost all of them, hole spaces must be controlled within 0.6-2 meters [2,3]. Densely distributed holes with large diameters would damage the existing pavement seriously. All of these requirement result in long construction and traffic closure time.

EC is a feasible alternative method to reinforce embankment of existing highway. Underground explosion compacts surrounding soil and creates a cavity within embankment. Then the cavity is backfilled with additional stronger and less compressive fillings such as gravel and cement grouting.

The use of blasting for the densification of granular soil has been developed for many years. However, this method has not been widely accepted mainly because it is still based on experience rather than theory[4]. Moreover, most of the previous studies have focused on densifying loose saturated sandy soil to mitigate its liquefaction or on compacting silt soils. It’s not practical to use them to guide EC construction design for loess strengthening, especially for loess embankment of

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existing road. There is little research on EC technique in loess. Study on EC in loess with #2 rock emulsion explosive is rarer. However, this kind of explosive is widely used in civil blasting in China at present. So it is very important to study its EC effect in loess.

It is difficult to carry out the field experiment of EC to strengthen embankment of existing highway because it is likely to affect the safety of pavement and side slope and result in more serious damage once experiment fails. Numerical simulation with computer software may be a good method to find the law of EC and to guide the design of construction scheme, but its accuracy and reliability has been concerned and worried by people. In order to verify the feasibility and reliability of the simulation of EC with ANSYS/LS-DYNA, two aspects including small-scaled outdoor experiment and numerical simulation are studied, and then their results are compared on four aspects: the volume of explosion cavity, soil density, the stress-time curves of soil and the velocity of explosion shock wave. These can be used for reference for the EC simulation based on actual embankment condition and geometry size.

Experiment

Experiment Field

Although it is impossible to perform experiment with the same soil as the embankment filling, they would better to be of the same kind, and have similar parameters. For this purpose, the experiment equipment was placed at the original site where the nearby embankment filling was taken from.

Experiment Process

The experiment container was a steel cylinder with 130 cm’s height and 170 cm’s inner diameter (Figure 1). The soil in cylinder was filled and tamped in 6 layers.

![Figure 1. Steel cylinder for experiment.](image1)

![Figure 2. Laying sensors.](image2)

was 3.8 cm. To collect and transmit the stress loading on soil by explosive shock wave, four MYD-8432D piezoelectric pressure sensors were embedded in soil at 26 cm, 36 cm, 46 cm and 56 cm away from the explosive tube center (Figure 2). TST5910 dynamic signal test and analysis system was used to store and display the stress data in the process of explosion and shock wave attenuation.

Moreover, in order to determine initial soil parameters through geotechnical tests, soil samples were taken with the cutting rings from the 3rd soil layer at different positions. Some of the soil parameters were measured immediately at the experiment field, including density, water content, maximum dry density, etc. Others (such as dynamic shear modulus, etc.) were obtained through laboratory tests.

When soil filling was completed, signal acquisition equipment was debugged. After all personnel had been evacuated to safe range, professional staff detonated explosive.

After explosion, the 1/4 section of soil was opened carefully to measure the volume of explosion cavity and to take soil samples at different position (Figure 3). Soil samples were used to determine
soil parameters after EC. Stress wave data were read from TST5910 dynamic signal test and analysis system.

Figure 3. Measuring the horizontal and vertical diameters of explosion cavity and taking soil samples.

**Numerical Simulation**

In this paper, ANSYS/LS-DYNA was used to simulate EC in loess.

**Finite Element Model**

Finite element model included 3 kinds of materials, including explosives, soil and air. The metricalation of the model was cm-g-μs, the unit of pressure was $10^{11}$ Pa, and the unit of velocity was $10^4$ m/s.

Considering symmetry, 1/4 of the physical model was analyzed to reduce the computational time demand. Model dimensions, boundary conditions, mesh and parts are shown in Figure 4 (a), (b) and (c).

![Finite Element Model Diagram](image)

(a) Cross-section view  (b) Side view (c) Meshed model

Figure 4. Model of explosion in soil.

**Material Model and Its Parameters**

High energy explosive material model, HIGH_EXPLOSIVE_BURN, was used to simulate rock emulsion explosive [5]. Its material parameters are shown in Table 1, where $\rho$, $D$ and $P_{CJ}$ are the density of explosive, detonation velocity and the pressure of blasting wave front, respectively. $A$, $B$, $R_1$, $R_2$, $\omega$ are explosive constants. $E$ is the internal energy density per unit initial volume[6,7,8]. Their values were derived from the experiment results of explosive manufacturer.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\rho$ [g/cm$^3$]</th>
<th>$D$ [m/s]</th>
<th>$P_{CJ}$ [GPa]</th>
<th>$A$ [GPa]</th>
<th>$B$ [GPa]</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$\omega$</th>
<th>$E$ [J/cm$^3$]</th>
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<tr>
<td>values</td>
<td>1.31</td>
<td>3200</td>
<td>9.90</td>
<td>214.40</td>
<td>0.182</td>
<td>4.20</td>
<td>0.90</td>
<td>0.15</td>
<td>4192</td>
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</table>

MAT_SOIL_AND_FOAM was used as the constitutive model of the soil[5]. Among its key parameters, $\rho$, $G$ and $K$ are density, shear modulus and unloading bulk modulus of soil respectively.
Their values were 1.83g/cm³, 13.4MPa and 29MPa respectively. $A_0$, $A_1$ and $A_2$ are constants of plastic yield function [6]. Their values were $1.79 \times 10^8$, 4950 and 0.0343 respectively.

The response behavior of air was described by null material model, MAT_NULL, and linear polynomial state equation. The state equation is as following [5]:

\[
P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2) E \quad (1)
\]

\[
\mu = 1/V - 1 \quad (2)
\]

Where $P$ is pressure acting on air. $C_0, C_1, C_2, C_3, C_4, C_5, C_6$ are the parameters of equation of state. $V$ is relative volume. $E$ is the density of internal energy. $\mu$ is a variable related to relative volume. The values of relevant material parameters are shown in Table 2, where $\rho$ is density. $E_0$ is the initial internal energy. $V_0$ is the initial relative volume[6,8].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\rho$[10$^3$g/cm³]</th>
<th>$C_0$[10$^{-6}$]</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>$C_6$</th>
<th>$E_0$[J/cm³]</th>
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<td>0.40</td>
<td>0.40</td>
<td>0.00</td>
<td>0.25</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

Simulation

In this simulation, 3D-SOLID164 solid element was used to mesh explosive, soil and air, and all of them were defined as ALE multi-material element so that all the materials could flow among meshes. Calculation time depends on the amount of explosive and the size of model. It’s considered suitable when blasting reaction is fully completed and the explosion cavity is in stable state and no longer develops any more during the time. It was 8000μs here.

Results Comparison

To verify the correctness of unit type, material model, parameters and so on, simulation results were compared with experimental results from four aspects, including the volume of explosion cavity, soil density, stress-time curve and wave velocity.

Comparison of Explosion Cavity Volume

The simulated volume of explosion cavity at 8000μs can be seen in Figure 5. For better observation, a mirror symmetry image was made, that was changing the original 1/4 model image into 1/2. Figure 6 is the curve of the volume of explosion cavity changing with time. It can be seen that explosion cavity develops very fast at the beginning, then slow down after 4000μs, finally it keeps stable after 5000μs.

Through a post processor, LS-PREPOST, 1/4 volume of simulated explosion cavity is 2950.48cm³. In the outdoor explosion experiment, the measured 1/4 volume is 2872.05 cm³. The difference between the numerical simulation result and the experimental result is -2.73%. It is acceptable. The actual volume of experimental explosion cavity should be larger than the measured volume because soil disturbance was inevitable in the process of opening the explosion cavity. The soil above cavity may fall back a little because of its gravity and the disturbance.

Comparison of Soil Density

In order to determine soil density and other soil parameters after EC, soil samples were taken at the position of 22cm, 37cm and 57cm away from cavity center when explosion cavity was opened (Figure3).

On the other hand, the soil densities at much more points were extracted from numerical simulation results and their scatter plot was plotted. For easy to compare, draw the measured soil densities before and after EC and the simulated soil density in Figure 7.

It can be seen from Figure 7 that soil density was significantly improved by EC. But the density of soil close to explosion cavity is not the maximum due to the stress there released some. It increases quickly until to the peak point and then decreases gradually with the attenuation of shock wave strength. Moreover, it can also be seen that the measured soil densities are slightly lower than
simulated values. This is due to the stress of soil released a little bit when the soil was opened after EC. On the whole, the simulated soil densities basically agree well with the experimental data after EC.

Figure 5. Simulated explosion cavity at 8000μs.

Figure 6. The simulated volume-time curve of explosion cavity.

Figure 7. Comparison of soil density.
Comparison of Stress-Time Curves of Soil

In the process of explosion compacting loess, four MYD-8432D sensors collected and transmitted the stress change in soil. TST5910 System recorded, stored and displayed the data (seen in Figure 8(a)). But Channel #6 of the system was out of order, so there are only three experimental stress-time curves in Figure 8(a). They express the stress changing with time at three points, including 26cm, 46cm and 56cm.

In simulation results, the stress-time curves of soil at four corresponding points of 26cm, 36cm, 46cm and 56cm away from explosive center were selected and drawn in Figure 8(b).

From Figure 8, it is found that the peak values on stress-time curves in (a) are in good agreement with that in (b).

Comparison of Shock Wave Velocity

The velocity of explosion shock wave is another reflection of explosion effect in soil. In the outdoor blasting experiment, shock waves were monitored by MYD-8432D sensors. The wave velocity was obtained by dividing the distance between two sensors by the time differences when the wave was captured. With 40g explosive, the measured wave velocity was 42.5m/s, while the numerical simulated one was 39.90 m/s. Both of them are in good agreement.

Summary

Based on the experiment and simulation of EC with #2 rock emulsion explosive in loess, and comparing simulated results with experimental results, there are four points to illustrate.

(1) The state equations and the material parameters of explosive, soil and air are correct in this model. In the future process of finite element modeling according to the actual embankment size of existing highway, air parameters in this paper can be directly referenced. If #2 rock emulsion explosive is selected as the explosive of EC, its parameters in this paper can also be referenced. But taking into account the differences between manufacturers and product batches, the parameters provided by manufacturer are prefer to be used. It is recommended to drill holes and take soil samples in embankment before modeling for EC, then model with soil parameters obtained from geotechnical tests. But the types and meanings of soil parameters here can be referenced. This will ensure that simulated results are in agreement with actual situation.

(2) In the process of finite element modeling in this paper, the methods of selecting unit type, setting boundary conditions and calculation time are correct. All of the others can be used to model according to the actual size of embankment except calculation time. The setting of calculation time
should be determined according to the weight of explosive and the size of model. It can also be adjusted in accordance with the calculation progress observed from volume-time curve of explosion cavity with post processing software until EC effect is fully finished and cavity volume doesn’t develop any more.

(3) It can be inferred that ANSYS/LS-DYNA can be used to simulate strengthening the embankment of highway with EC technique and guide the design of construction scheme. But in the future research, finite element model should be built up according to the actual embankment size of highway. With this model, the effects of explosive amount, the way of burying explosive, soil properties and so on could be furtherly simulated and analyzed so as to guide the construction of EC.

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