Dynamic Characteristics and mud Pumping Mechanism of Graded Gravel Under Cyclic Loading

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ABSTRACT
The study investigates dynamic behavior of graded gravel subjected to long-term load in high speed railway as well as requirements for graded gravel basement. Dynamic experiments on graded gravel were carried out systematically through large scale triaxial equipment. Deformation mechanism of graded gravel subjected to cyclic loading was analyzed under different conditions of confining pressure, water content and dynamic stress with consideration of influent factors. Appropriate models for cumulative deformation of graded gravel were derived. Also, preliminary analysis of formation and development of mud pumping in the graded gravel basement was conducted. The results of the research: critical dynamic-to-static stress ratio $K_r = 0.4$ can be used as a criteria of dynamic strength to design graded gravel basement of high-speed railway; graded gravel subjected to cyclic load has highly stable strength at optimum water content. However, the stability of strength is reduced at saturated and supersaturated state. Comparing with the cumulative deformation at optimum water content, the deformation at saturated and supersaturated state is 1.7 and 2.85 times larger respectively and increase continuously until to failure. Therefore, the bearing capacity of the basement is reduced, leading to the structure damaged easily.

KEYWORDS: Graded gravel; Triaxial test; Long-term dynamic load; Cumulative deformation; Critical dynamic stress; Mud pumping

INTRODUCTION
Graded gravel is unbound granular material, with good strength, deformation and permiable ability, quite ideal material for basement of ballastless high speed railway. However, in stages of transportation, construction and operation, breakage of graded gravel particle caused by mechanical impact and environmental effect occurs (Yasuda et al. 1997). As the result of the breakage, the increased content of fine aggregate easily leads to damage of the basement. Especially, the increase of fine aggregate content under changing environment condition (such as infiltration of surface water through cracks) causes water content of the basement increased, the
strength of the basement is reduced as the result) has very negative influence on the basement, likely causes mud pumping even separation between surface layer and subgrade layer (Muramoto and Nakamura 2011, Muramoto et al. 2006, Zhang et al. 2014, Zhang et al. 2002), as shown in Figure 1. Hence, dynamic performance of graded gravel is the key feature for stability of roadbed of ballastless high speed railway.

![Figure 1: The failure of mud pumping in ballastless track](image)

Currently, the number of researches on mud pumping in graded gravel subgrade of ballastless roadbed subjected to long-term load is relatively small. Especially, few researches consider relationship between deterioration of graded gravel subgrade and effect factors such as amplitude of dynamic stress, the number of load cycles, water content, etc. This study, through large scale dynamic triaxial test under different conditions of confining pressure, water content and dynamic stress, investigated dynamic behavior of graded gravel subjected to cyclic load. It is a fundamental study for dynamic stability of roadbed of high speed railway under long-term load.

**EXPERIMENTAL SCHEME**

**Experimental sample and method**

The testing material was collected from the field of railways "Central and Southern Railway Shanxi channel". Maximum density $\rho_{\text{dmax}} = 2.35\text{g/cm}^3$, optimum water content $\omega_{\text{opt}} = 4.85\%$ were determined through the experiments using large electric compaction apparatus DJ30-5. Triaxial specimens were produced by using the coning and quartering method, the material was mixed evenly at the optimum water content and stored in a closed container in 2 hours to ensure uniform distribution of water content in the material. After that, the material was divided into separately compacted layers to obtain requested degree of compaction $K = 0.95\%$ following to the specification SL 237-1999 (Specification of soil test in China). The specimens after production have the shape of cylinder and the dimension of $\Phi300 \times h600\text{mm}$.

**Experimental equipment**

The large scale triaxial equipment FSC5-2000 electro-hydraulic servo was used to carry out the experiments. The device includes following main components: loading system, control system of confining pressure and data collection system, as shown in Figure 2.
Experimental method

Confining pressure is divided into 4 level (15, 30, 45 and 60kPa) to take into account the actual stress state with depth dependence of the subgrade of high speed railway. Firstly, applying confining pressure at the specified value and kept stable in 30 minutes. Then axial stress (15kPa) was applied in static state to ensure no pulse impact appeared. After static loading stage, cyclic dynamic loading stage was conducted. Five levels of dynamic load were applied at each confining pressure to identify the ultimate state. Sine wave load with the frequency of 5Hz was used to simulate running train load (as Figure 3), with loading control by stress and the number of loading cycles from 10,000 to 20,000.

Table 1: The conditions of experiment

<table>
<thead>
<tr>
<th>Confining pressure $\sigma_3$ (kPa)</th>
<th>Dynamic stress $\sigma_d$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>93</td>
</tr>
<tr>
<td>30</td>
<td>108</td>
</tr>
<tr>
<td>45</td>
<td>122</td>
</tr>
<tr>
<td>60</td>
<td>136</td>
</tr>
<tr>
<td>147</td>
<td>168</td>
</tr>
<tr>
<td>190</td>
<td>211</td>
</tr>
<tr>
<td>201</td>
<td>229</td>
</tr>
<tr>
<td>258</td>
<td>286</td>
</tr>
<tr>
<td>255</td>
<td>290</td>
</tr>
<tr>
<td>305</td>
<td>325</td>
</tr>
<tr>
<td>361</td>
<td>393</td>
</tr>
<tr>
<td>308</td>
<td>351</td>
</tr>
<tr>
<td>393</td>
<td>436</td>
</tr>
</tbody>
</table>
CHARACTERISTICS OF GRADED GRAVEL UNDER CYCLIC LOADING

Cumulative deformation

The residual deformation appeared at each loading and unloading step in the graded gravel subjected to cyclic load. Figure 4 shows the relationship curves between the cumulative deformation of the graded gravel and the number of dynamic load cycles in accordance with different confining pressures.
Figure 4: Relationship curves between cumulative deformation and the number of load cycles

**Table 2: Cumulative deformation classification of different status characteristics**

<table>
<thead>
<tr>
<th>State division</th>
<th>Heath, Cai et al.</th>
<th>Wang</th>
<th>Werkmeister</th>
<th>Minasian</th>
<th>Hoff</th>
<th>Liu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation state</td>
<td>Plastic shakedown</td>
<td>Stable state</td>
<td>Stable state</td>
<td>Plastic state</td>
<td>Elastic state</td>
<td>Fast stable</td>
</tr>
<tr>
<td>Breakdown state</td>
<td>Plastic creep shakedown</td>
<td>Attenuation state</td>
<td>Critical state</td>
<td>Plastic state</td>
<td>Breakdown state</td>
<td>Long-term stable</td>
</tr>
</tbody>
</table>

From the experiment result shown in the Figure 4, development trend of the cumulative deformation curves versus the number of load cycles can be divided into 2 states including: attenuation state and breakdown state. The curves of the attenuation state at initial loading cycles indicate large amount of deformation including residual and resilient deformation. After a specific number of load cycles, only resilient rather residual deformation is generated and the cumulative deformation is gradually stable. The curves of the breakdown state increases nonlinearly due to the growth of number of load cycles. After a specific number of large dynamic load, the experimental sample was destroyed partly, the deformation increased continuously until the sample was completely damaged. It can be seen that the dynamic triaxial tests in this research show similar results with those in the studies of Heath et al. 1972, Cai and Cao 1996, Jiang et al. 2010, Kong et al. 2012, which provides basic understanding to carry out intensive investigation on development law of the cumulative deformation in graded gravel subgrade.

**Cumulative deformation calculation model**

The experimental results indicate that changes of cumulative deformation curves caused by alternation of confining pressure are not very large. Hence in this research, confining pressure $\sigma_3$ is applied at 30kPa to determine the appropriate calculating model for the cumulative deformation curve. Apart from effect factors such as level of dynamic load, the number of load cycles, the cumulative deformation of graded gravel is also dependent on physical properties of the graded gravel.

Figure 5 indicates classification of the cumulative deformation curves of graded gravel with confining pressure $\sigma_3$ of 30kPa. Also, appropriate calculating models are shown in the figure.
The cumulative deformation curve of the attenuation state, with regardless the initial part, can be expressed through the model Stewart 1986 as following:

\[ \varepsilon = \alpha_0 (1 + \beta_0 \ln N) \quad \text{or} \quad S = \alpha + \beta \ln N \]  

(1)

Here: \( \alpha, \beta \) are factors for considering to level of dynamic load and the material properties respectively; \( N \) is the number of load cycles.

The cumulative deformation curve of the breakdown state can be expressed through the model Monismith 1975 as following:

\[ \varepsilon = AN^b \quad \text{or} \quad S = AN^b \]  

(2)

Here: \( A, b \) are factors for considering to level of dynamic load and the material properties respectively; \( N \) is the number of load cycles.

Table 3 shows regression curves and simulation parameters for the cumulative deformation of graded gravel subjected to cyclic load according to the number of load cycles.

<table>
<thead>
<tr>
<th>Dynamic stress ( \sigma_d ) (kPa)</th>
<th>Regression equation</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Attenuation state</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>108</td>
<td>( S = -0.0716 + 0.0478 \ln N )</td>
<td>0.9333</td>
</tr>
<tr>
<td>168</td>
<td>( S = -0.2862 + 0.0911 \ln N )</td>
<td>0.9510</td>
</tr>
<tr>
<td>229</td>
<td>( S = -1.1328 + 0.2358 \ln N )</td>
<td>0.9854</td>
</tr>
<tr>
<td><strong>Breakdown state</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>290</td>
<td>( S = 0.0215 N^{0.4937} )</td>
<td>0.9907</td>
</tr>
<tr>
<td>351</td>
<td>( S = 0.0199 N^{0.5551} )</td>
<td>0.9989</td>
</tr>
</tbody>
</table>

\( R \) for the correlation coefficient.

For the formula (1), the value of \( \alpha \) spreads in a range from 0.0716 to 1.1328, which refers that \( \alpha \) will change so much due to the differences of loading level. Factor \( \beta \) also varies in relatively wide range from 0.0478 to 0.2358. It indicates that \( \alpha, \beta \) factors are not only affected by dynamic stress state, the number of load cycles but also affected significantly by physical conditions.
properties of the material. In the formular (2), varying ranges of factors A and b are quite small as 0.0199 ∼ 0.0215 and 0.4937 ∼ 0.5551 respectively. It would be explained that large dynamic load accelerated development of strain-softening of the material and the material was destroyed rapidly, which led to decrease of the effects of the dynamic loading level and the physical properties.

**Critical dynamic stress**

"Critical dynamic stress" of graded gravel is a limit value of dynamic stress at which the material transfers from attenuation state to breakdown state. If dynamic stress is smaller than the critical dynamic stress of the basement, the cumulative deformation can be effectively controlled. Larew and Leonards 1962 mentioned that failure state of grade gravel subjected to cyclic load is determined by the number of load cycles and the moment when rate of deformation begins to increase.

In the research, the critical dynamic stress of graded gravel is determined with confining pressure of $\sigma_3 = 30$ kPa. In semilog coordinate, curves of relationship between cumulative deformation slope ($\Delta S/\Delta \lg N$) and the number of load cycles in accordance with each dynamic stress value are shown in Figure 6. When dynamic stress reaches to the critical stress, the slope of cumulative deformation curve becomes zero. Liu 2013 supposed that cumulative deformation slope ($\Delta S/\Delta \lg N$) and the number of load cycles will have linear relationship when dynamic stress is approximate critical stress value. Therefore, linear functions expressing relationship between dynamic stress and cumulative deformation slope were created and the critical dynamic stress was defined as $\sigma_{dc} = 235$ kPa, as the result. The static ultimate stress of the same specimen is 620 kPa, determined by static triaxial test. Hence, ratio of dynamic-to-static critical stress is defined as the following:

$$K_f = \frac{\sigma_{dc}}{(\sigma_1 - \sigma_3)} = 0.4$$

(3)

**Figure 6:** Relationship between cumulative deformation slope and number of load cycles

Compared to the related research of Cai 1999, $K_f \leq 0.6$, the critical dynamic stress determined in this study is reliable, can be used as dynamic strength criteria for designing graded gravel basement of high speed railway. The $K_f$ index can be used to reflect whether the deformation of graded gravel subgrade subjected to dynamic load is stable or not. If the subgrade withstands a dynamic load having ratio of dynamic-to-static critical stress which is
greater than the $K_r$ index, the cumulative deformation will increase continuously following to growth of load cycle number until the subgrade is damaged.

### Influence of confining pressure

As shown in Figure 7, the relationship between critical dynamic stress and confining pressure is nonlinear, critical dynamic stress increases due to the growth of confining pressure. Critical dynamic shows an increase by 37% from 219kPa to 299kPa following to the change of confining pressure from 15kPa to 60kPa. It indicates that confining pressure has significant influence on critical dynamic stress. It is explained that contact between aggregate particles became more tight due to the increase of confining pressure, which caused dynamic strength and resilient deformation ability improved. Unfortunately, in reality, confining pressure acting on the graded gravel basement of high speed railway is relatively small because of limited height of the backfill. Therefore, dynamic bearing capacity of the basement has to be considered and improved.

![Figure 7: Relationship between critical dynamic stress and confining pressure](image)

Considering the critical state of graded gravel as a failure state, the principal stresses are obtained as $\sigma_{1d} = \sigma_3 + \sigma_{dc}$ and $\sigma_{3d} = \sigma_3$. Hence, stress Mohr's circle and the failure dynamic strength line are plotted to determine the strength parameters at dynamic state: cohesion $C_d = 52.5$ kPa and internal friction angle $\Phi_d = 29.7^0$. The same samples were conducted static triaxial tests to define the strength parameters under static condition: $C_s = 81.5$ kPa and $\Phi_s = 49.3^0$. It is realized from the above results that the shear strength at dynamic state is smaller than that at static state. The reason is that when graded gravel is subjected dynamic load, increase of fatigue effect results in decrease of dynamic shear strength. This comment is consistent with the research result of Shen and Zhang 1998.
Laboratory experiment by Graded graver of mud pumping mechanism

Laboratory experiment by mud pumping were preliminarily analyzed

The basement of the ballastless high speed railway is composed of graded gravel with relatively high density and strength, which withstands dynamic load directly. In current design specifications of high speed railway, parameters of the graded gravel such as density, dimension of aggregate particles, etc. are required strictly in order to prevent the excessive deformation due to long-term load. Also, high permeability is important criteria of graded gravel. Graded gravel comprises coarse aggregate (d ≥ 5mm) and fine aggregate (d < 5mm) (Deng 1997). The skeleton formed by coarse aggregate particles is the main component to support external force. Fine aggregate plays a role in filling up the voids between the coarse aggregate particles, which effects directly on permeability of the aggregate. The permeable ability is reduced following with the growth of silt content (d ≤ 0.1mm) in fine aggregate (Deng 1997) and vice versa.

Dynamic triaxial tests were carried out with different conditions of water content to investigate deformation behaviour of graded gravel subjected to long term load. During sample compacting process, part of the aggregate was broken and fine aggregate content increased gradually. In addition, being subjected to cyclic load, the aggregate was not only relocated but also broken (Yasuda et al. 1997) leading to increase of fine aggregate, particularly silt content. At saturation state (ω_s = 7.37%) and supersaturation state (ω_o = 8.64%), excess pore water pressure was created due to effect of cyclic dynamic load. After that, the dissipation of water pressure by the seepage was accompanied with the silt, resulting in mud pumping.

MUD PUMPING MECHANISM RESULT ANALYSIS

Particle grading size analysis

The results of grain size analysis with original sample and sample after dynamic loading are shown in Figure 8 and Table 4. It can be seen that percentage of passing of coarse aggregate was basically unchanged, while at the 0.1mm sieve there was small growth of passing by 0.8% from 1.4% at stage of before loading to 2.2% at stage of after dynamic loading.
For graded gravel at saturated state and supersaturated state, excess pore water pressure was developed due to loading stage. After that the pore water drained to relieve the excess pore water pressure in it. Cohesive and internal friction angle of graded gravel at saturated state and supersaturated state are gradually reduced (Li et al. 2009), the reasons are the movement of pore water under dynamic load and mud pumping caused by combination of silt and water.

After loading test, the sample was divided into 4 layers from the top to the bottom to carry out the sieving test. The result in Table 5 indicates that there is very small difference even no unchanged in passing percentage of coarse aggregate between the layers. Whereas the percentage of fine aggregate has a trend of increase considering from the bottom layer to the top layer, in which the passing of the top layer (A layer) is 1.04 time (size 0.5mm) and 2.2 times (size 0.1mm) larger than that of the bottom layer (D layer). It is explained that fine aggregate was washed away due to pore water flow, especially combination of silt component and water flow under dynamic load created mud pumping.

### Table 4: Particle size of graded gravel

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Before the test</th>
<th>After the test</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>100</td>
<td>95.7</td>
</tr>
<tr>
<td>31.5</td>
<td>95.7</td>
<td>95.7</td>
</tr>
<tr>
<td>22.4</td>
<td>84.8</td>
<td>84.8</td>
</tr>
<tr>
<td>7.1</td>
<td>52.6</td>
<td>52.6</td>
</tr>
<tr>
<td>1.7</td>
<td>24.8</td>
<td>24.7</td>
</tr>
<tr>
<td>0.5</td>
<td>12.2</td>
<td>12.3</td>
</tr>
<tr>
<td>0.1</td>
<td>1.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>

For graded gravel at saturated state and supersaturated state, excess pore water pressure was developed due to loading stage. After that the pore water drained to relieve the excess pore water pressure in it. Cohesive and internal friction angle of graded gravel at saturated state and supersaturated state are gradually reduced (Li et al. 2009), the reasons are the movement of pore water under dynamic load and mud pumping caused by combination of silt and water.
As shown in Figure 10, surface of the sample before the loading test has a relatively uniform distribution. After loading test, the surface changed clearly in distribution and mud appeared. The aggregate skeleton at the side area of sample was exposed because the fine aggregate at this area was removed by water flow. At centre area, since the mud was not washed away due to the boundary constraint then concentration of fine aggregate occurred.
The influence of moisture state of graded gravel

Figure 11 and Figure 12 show the influence of water content on the deformation and the critical dynamic of graded gravel under condition of confining pressure $\sigma_3 = 30\text{kPa}$, dynamic stress $\sigma_d = 229\text{kPa}$.

![Graph showing deformation and critical stress](image)

**Figure 11:** $\sigma_3 = 30\text{kPa}$, $\sigma_d = 229\text{kPa}$, $S - \lg N$ curves under different moisture content

![Graph showing deformation slope and load cycles](image)

**Figure 12:** $\sigma_3 = 30\text{kPa}$, $\sigma_d = 229\text{kPa}$, Relationship between cumulative deformation slope and number of load cycles

Obviously, as shown in Figure 11 and Figure 12, water content has significant effect on the cumulative deformation and the critical dynamic stress. At the optimum content, the cumulative deformation decreased following to growth of the number of load cycles, the deformation
obtained maximum value of 1.21mm when the number of load cycles was 20,000. The state is considered as ultimate state as the slope of cumulative deformation curve remains zero. It is found that the graded gravel at optimum water content did not reach to ultimate state. Whereas, in cases of saturated and supersaturated water content, the cumulative deformation increased continuously until to damage. The cumulative deformation values of the two later cases were 1.7 and 2.85 times larger than that of the optimum content case at the moment when the number of load cycles was 20,000. It can be explained that, when grade gravel at saturation or supersaturation was subjected to dynamic load, pore water pressure increased continuously, also growth of fatigue occurred, as the result shear strength was gradually reduced leading to damage. Therefore, surface water drainage must be solved immediately to avoid soaked surface, which is a reason causing the subgrade saturated.

CONCLUSIONS

The research by large scale dynamic triaxial test carried out investigation dynamic behavior and development of mud pumping of graded gravel basement in high speed railway under condition of dynamic cyclic load. The following conclusions are derived:

1. The relationship curve between cumulative deformation and the number of load cycles, according to change of cyclic load, can be divided into 2 states as following: attenuation state and breakdown state. The curve of the attenuation state can be expressed through the model Stewart 1986 $S = a + \beta \ln N$, the curve of the breakdown state can be expressed through the model Monismith 1975 $S = AN^b$.

2. With the same number of load cycles, the larger dynamic stress was applied the larger cumulative deformation became; the cumulative deformation slope increased following to the increase of dynamic stress; relatively large dynamic stress accelerated development of strain-softening of the testing material.

3. The dynamic-to-static stress ratio $K = \sigma_{dc}/\sigma_s = 0.4$ can be used as dynamic strength criteria for designing graded gravel basement of high speed railway.

4. The dynamic shear strength of graded gravel was smaller than the static shear strength because increase of fatigue effect due to dynamic loading causes the shear strength decreased gradually.

5. Cohesive and internal friction angle of graded gravel at saturated state and supersaturated state were gradually reduced due to the movement of pore water under dynamic load and mud pumping caused by combination of silt and water.

6. At the optimum content, the cumulative deformation obtained maximum value of 1.21mm and ultimate state did not occur when the number of load cycles was 20,000. Whereas, in cases of saturation and supersaturation, the deformation increased continuously until to damage and the values of cumulative deformation in these 2 cases were 1.7 and 2.85 times larger than that of optimum water content case at the moment when the number of load cycles was 20,000.
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REFERENCES


