# Numerical Analysis on Bearing Capacity of Double-Layer Foundation Under Uniform Load of Adjacent Rectangles

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**Abstract:** The gravel cushion is a certain thickness of gravel layer laid on the foundation, which is composed of uniform bulk materials and it has the characteristics of good compaction performance, high filling density, high shear strength, small deformation, high bearing capacity, etc. Satisfactory results were obtained in various fields of civil engineering. In the operation site of crawler cranes, such as some electric power projects and heavy-load accumulation sites, most of the foundations are also double-layer foundations that have been replaced. However, the stress distribution and load-bearing performance of the double-layer foundation under the crawler crane operation need to be further studied. In this study, the QUY80 crawler crane was simplified into uniformly distributed loads on adjacent rectangles of equal size on the foundation. The finite difference FLAC3D software was used to establish a three-dimensional foundation model. For analysis.

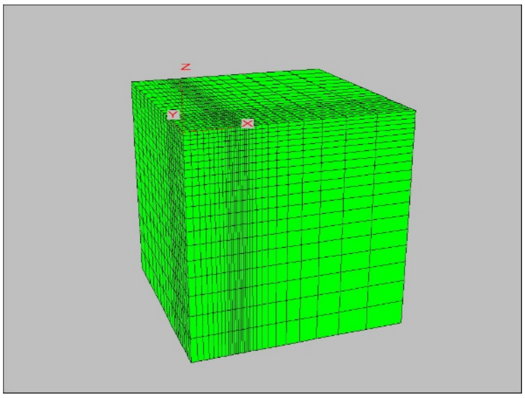
## 1. Model Establishment and Related Calculation Parameters

QUY80 crawler crane is a commonly used type of lifting equipment in engineering construction. Through querying QUY80 factory instruction manual and reading related materials，The basic parameters of the crawler crane under the maximum lifting weight are shown in Table 1, L is the length of the single track grounding area, b is the width of the single track grounding area, and B is the track pitch between the tracks.

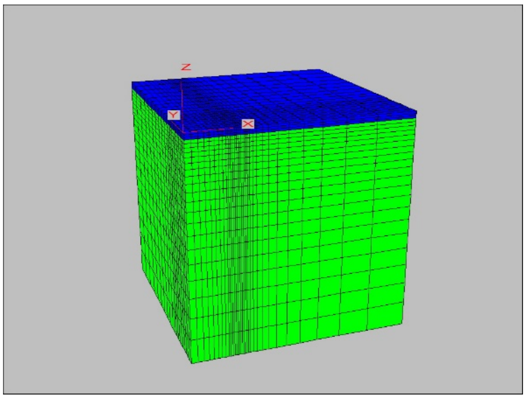
**Table 1. QUY80 basic parameters**

| L/m | b/m | B/m |
|---|---|---|
| 5.48 | 0.86 | 4.2 |

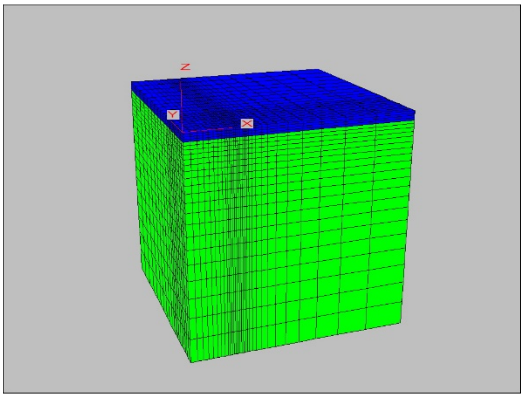
During the operation of the crawler crane, considering the symmetry of the load of the foundation and the upper crawler grounding area, the foundation model is selected to calculate 1/4 of the actual model. Using FLAC3D software to establish foundation model[1]， The origin of the X-Y axis and the coordinate axis are shown in the figure below，The Z axis is positive, the foundation model is below the horizontal plane, and 10m each in the horizontal direction of the calculated area after trial calculation, the X direction is ten times the width of the track grounding area, the inner side is 1.67m, the outer side is 7.47m, the length of the track grounding area The direction periphery is 7.26m, and the Z direction is also 10m. In the analysis, in order to reduce errors caused by structural dimensions such as track height and physical and mechanical parameters, a track model is not established. The grounding area of the crawler is the simultaneous encryption area in the x and y directions on the horizontal plane z = 0, that is, 0 m $<x<1.67$ m and 0 m $<y<2.74$ m. The replacement thickness of the gravel cushion is 0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.2m. The foundation model is shown in Figure 1. Blue represents the gravel cushion after replacement, and the green area represents the general clay soil underneath. Peripheral X = 0, Y = 0 lateral constraints, no displacement in the horizontal direction and the surface where X = -10, Y = 10 boundary is located only constrains the vertical displacement of the surface, rolling bearing is considered.



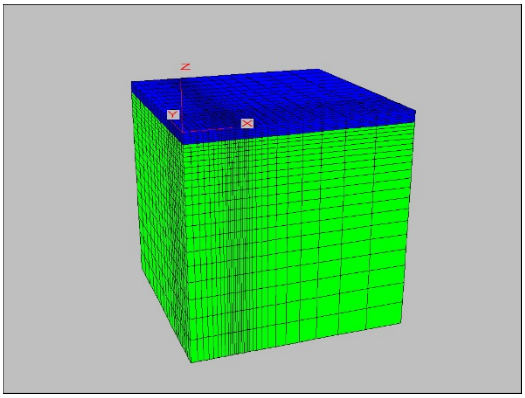
(A) 0m gravel cushion



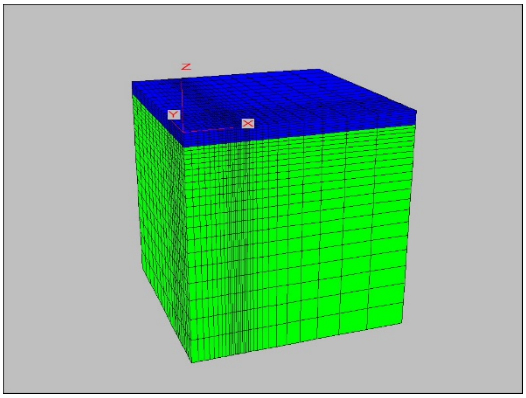
(B) 0.3m gravel cushion



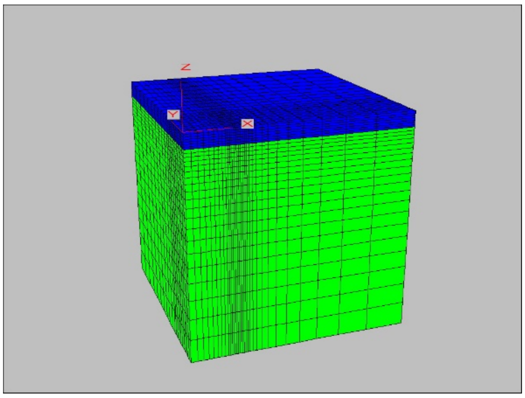
(C) 0.4m gravel cushion



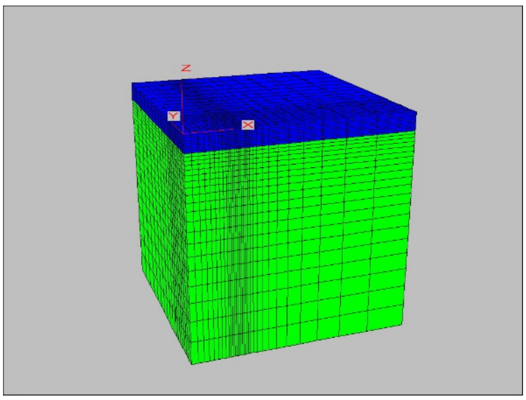
(D) 0.5m gravel cushion



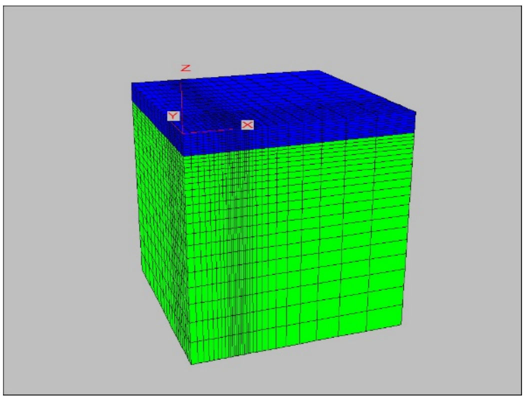
(E) 0.6m gravel cushion



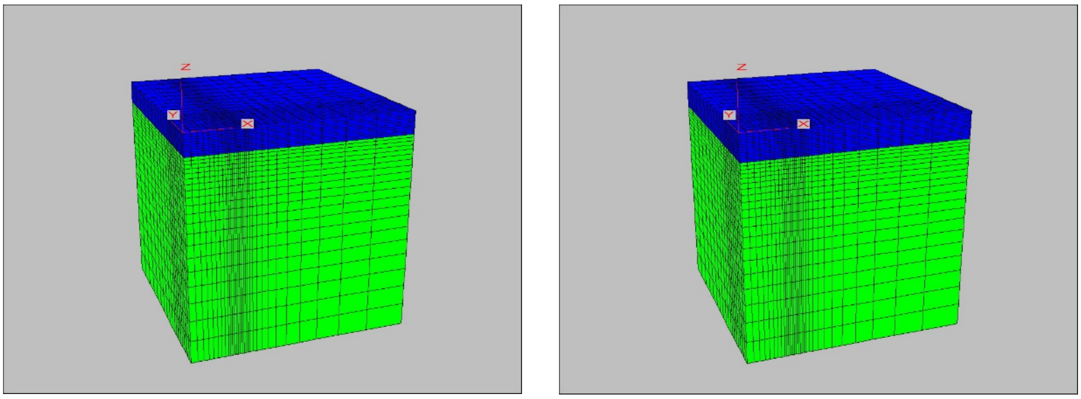
(F) 0.7m gravel cushion



(G) 0.8m gravel cushion



(H) 0.9m gravel cushion



(I) 1m gravel cushion (J) 1.2m gravel cushion

**Figure 2.** Model diagram of double-layer foundation

The constitutive relationship of the soil is selected by the Moore-Coulomb constitutive model[3], and by consulting the empirical data on rock and soil in the "Engineering Geology Manual"[4], the gravel cushion and the underlying general clay soil are finally determined The physical parameters are listed in Table 2 below.

**Table 2.** Soil calculation parameters

| Soil mass | $\rho\left(kg/m^3\right)$ | $K\left(Mpa\right)$ | $G\left(Mpa\right)$ | $c\left(Kpa\right)$ | $\varphi\left(^o\right)$ | $\upsilon$ |
|---|---|---|---|---|---|---|
| Gravel cushion | 2300 | 22.22 | 16.67 | 0 | 40 | 0.2 |
| Cohesive soil | 2000 | 7.58 | 3.91 | 20 | 20 | 0.28 |

First, after the analysis model is established, a phased elastoplastic solution method is used to obtain the initial stress state. Then enter the simulation solution process of the ultimate bearing capacity of the double-layer foundation. The loading method is displacement loading. The crawler grounding area is gradually loaded by controlling the displacement of the node. The speed of the node is 2 × 10-5m / step. The average value of the ground reaction force received determines the applied external load, thereby obtaining the load-displacement curve. The damaged area of the local foundation soil developed to the surface and interpenetrated with each other and stopped loading. At this time, the change range of load p value is getting smaller and smaller, and the foundation settlement s continues to increase, so it is judged that the foundation soil is damaged.

## 2. Result Analysis

### 2.1. Load-displacement Curve

According to the simulation results of replacing the gravel cushion with different thickness, draw the load (p) and settlement curve (s). For the steep deformation curve, select the load value corresponding to the second turning point of the p-s curve as the ultimate bearing capacity of the foundation. It shows a gentle deformation curve, and the s-lgt curve needs to be integrated to further determine the limit load value. The calculated p-s curves for different thickness gravel cushions are shown in Figure 2 below.

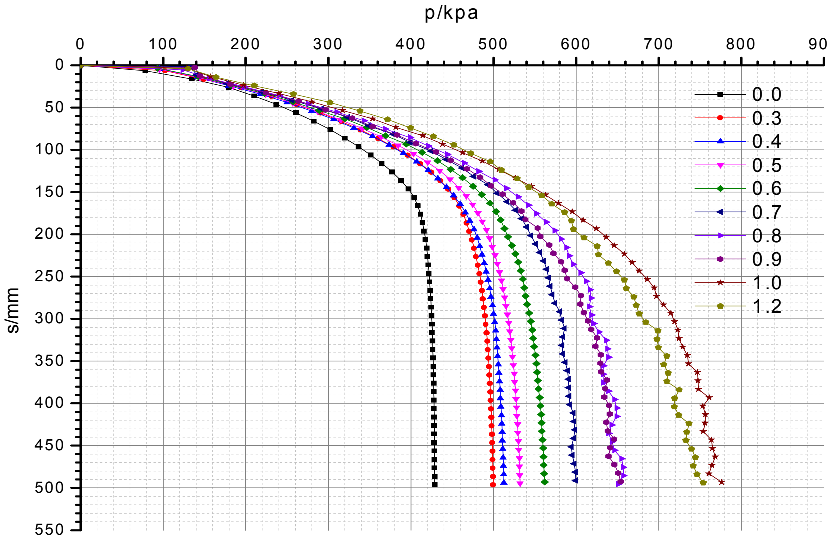



**Figure 2.** p-s curves of gravel cushion with different thickness

It can be seen from Figure 2 that the p-s curve of the foundation after replacing the gravel cushion with different thickness basically undergoes the compaction stage, shear stage and the stage proposed by Gersevanov During the failure stage, but for the gravel cushion from 0.7 to 1.2m, special conditions appear in the curve, and a "step" curve appears in the curve[5]. The reason for this kind of buckling phenomenon is mainly because the composite foundation of gravel cushion is a heterogeneous structure of gravel and soil, the deformation modulus is different, and a series of combined changes occur inside the material under load. Under the action of temporary plastic load, part of the crushed stone is squeezed into the soil, and the skeleton structure of the soil is rearranged and combined to facilitate stress diffusion. At the same time, the p-s curve reflects the rapid increase of strain, and then the soil foundation tends to be dense, the deformation decreases rapidly, and the curve becomes flat.

The load corresponding to the inflection point at the boundary between the shear stage and the failure stage in the respective p-s curves is selected as the ultimate bearing capacity of the composite foundation with different gravel cushion thickness.

**Table 3.** Table of ultimate bearing capacity of composite foundation with gravel cushion

| Thickness of gravel cushion（m） | 0 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Ultimate bearing capacity（KPa） | 420 | 490 | 510 | 530 | 550 | 580 | 600 | 620 | 720 | 700 |

Analysis and comparison of the ultimate bearing capacity of the foundation under different thickness of the gravel cushion can be found that the ultimate bearing capacity of the foundation without replacement of the gravel cushion is 420 KPa. After the replacement of the gravel cushion, the bearing capacity of the foundation is obvious Increase, when the thickness of the gravel cushion is within 1m, as the thickness of the gravel cushion increases, the ultimate bearing capacity of the foundation increases linearly, as shown in Figure 3 below. When the thickness of the gravel cushion is 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, the ultimate bearing capacity of the foundation is increased by 17%, 22%, 26%, 31%, 38% sequentially, 43%, 48%, 71%. However, when the crushed stone cushion is 1.2m, the ultimate bearing capacity of the foundation is 700 KPa, which is lower than the 720 KPa when the crushed stone cushion is 1m. The damage range is limited to the gravel cushion. The failure of the foundation is a single-layer foundation failure. When the gravel cushion is 1m, the shear failure range of the foundation includes the gravel cushion and the following soil layer, the boundary framework between the gravel and the soil layer The structure is rearranged and combined, the soil gradation is better, the compactness is improved, and the corresponding ultimate bearing capacity is larger than that of the single-layer foundation.

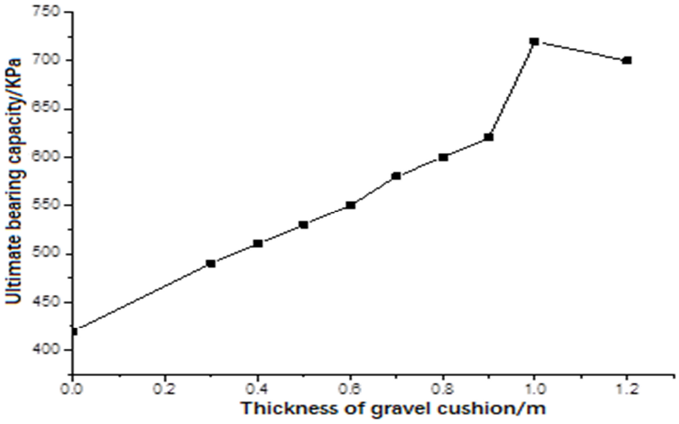


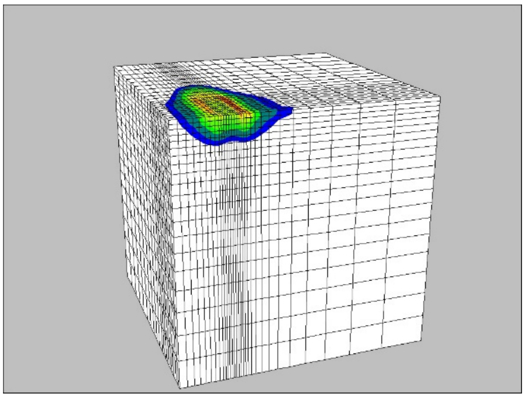

**Figure 3.** Variation of ultimate bearing capacity with cushion thickness

After replacing the gravel cushion, due to the larger deformation modulus of the gravel cushion, the settlement of the foundation is improved. When the load p = 300 KPa, the thickness of the gravel cushion is 0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, corresponding to the foundation settlement of 74mm, 61 mm, 60 mm, 59 mm, 57 mm, 55 mm, 54 mm, 53 mm, 48 mm, 43 mm, replacement of gravel After the cushion, the settlement of the unreplaced foundation was reduced by 18%, 19%, 22%, 23%, 26%, 27%, 28%, 35% and 42% respectively.

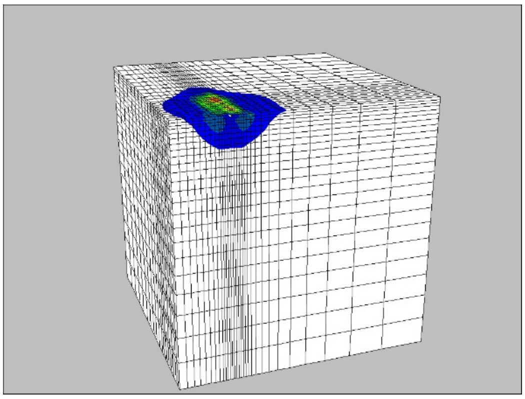
### 2.2. Analysis of Foundation Failure Mode

The foundation soil is a natural body, and there are many variable factors. Generally speaking, the failure mode of the foundation is mainly represented by shear failure. The factors that affect the failure mode of the foundation include soil conditions and foundation conditions. The conditions of the foundation soil include the type, density, water content, compressibility and shear resistance of the foundation soil Strength; foundation conditions include foundation form, burial depth, size [5].

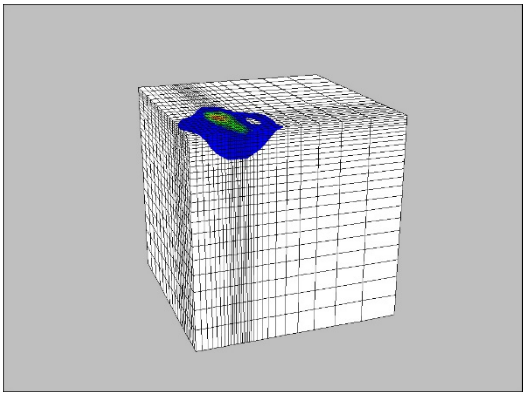
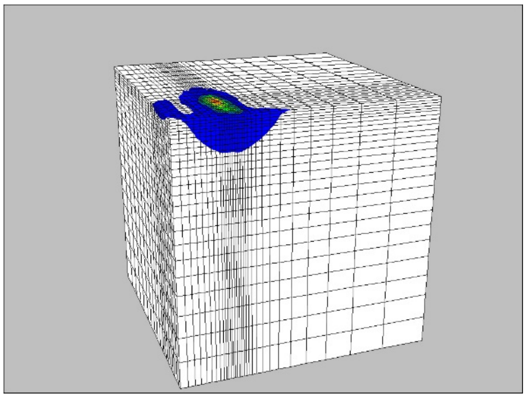
The failure mode of the double-layer foundation after replacing the gravel cushion is nothing more than overall shear failure, local shear failure and punching shear failure. The specific failure mode has a great relationship with the relative thickness of the upper hard soil layer (thickness of gravel cushion / width of foundation). In this paper, the finite difference software FLAC3D is used for the foundation under different thickness of gravel cushion the destruction mode was simulated. In the numerical simulation, the shear strain rate cloud diagram represents the shear failure plane of the soil. The simulation results are compared with the shear strain rate in the area greater than 5e-6 as the failure surface of the foundation. The results are shown in Figure 4 below.



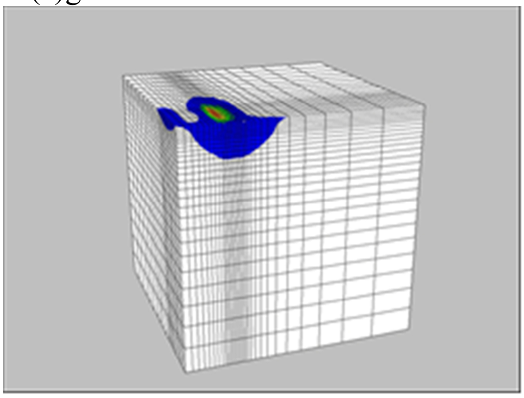
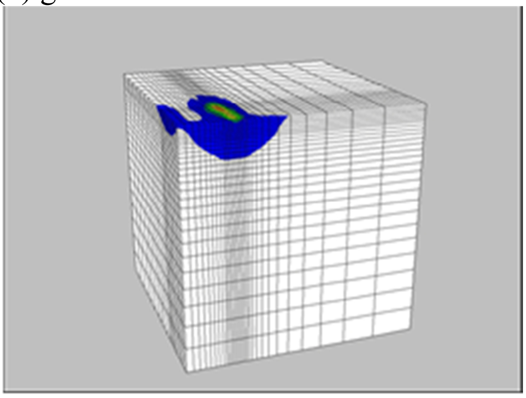
(a) gravel cushion 0.0m foundation



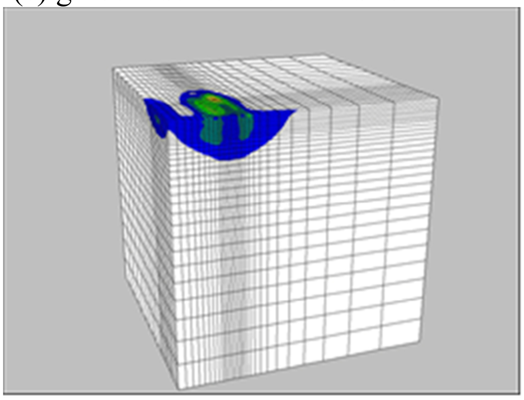
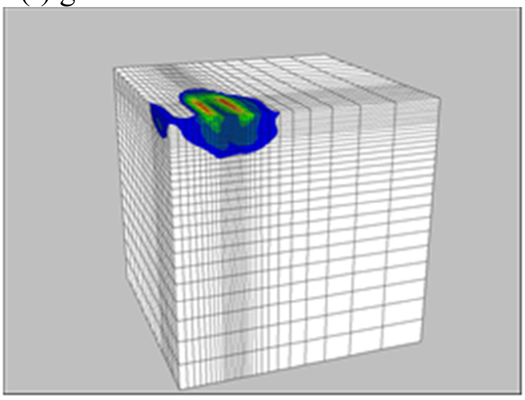
(b) gravel cushion 0.3m foundation

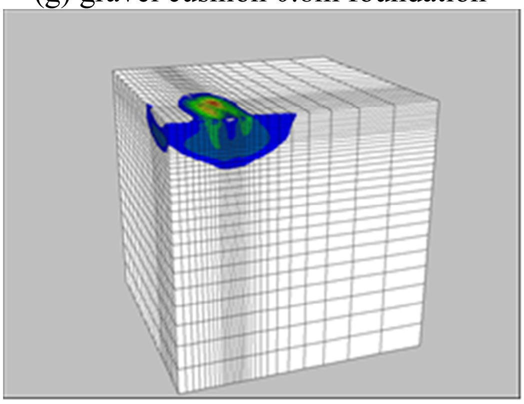
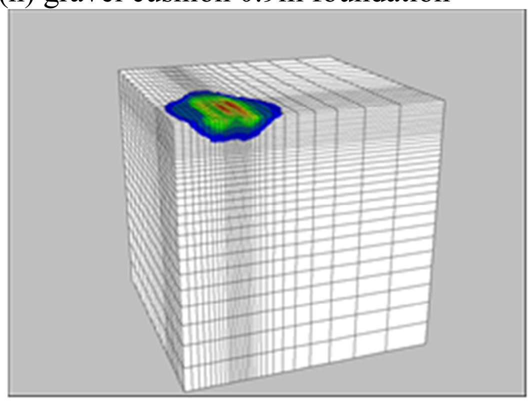
(c)gravel cushion 0.4m foundation (d) gravel cushion 0.5m foundation

(e) gravel cushion 0.6m foundation (f) gravel cushion 0.7m foundation

(g) gravel cushion 0.8m foundation (h) gravel cushion 0.9m foundation

(i) gravel cushion 1.0m foundation (j) gravel cushion 1.2m foundation

**Figure 4.** Shear strain rate cloud diagram of double-layer foundation

Fig. 4 (a) shows the cloud diagram of shear strain rate of homogeneous foundation. It can be seen from the figure that the failure mode of the homogeneous soil foundation is overall shear failure, and a wedge formed below the loading area penetrates into the soil and squeezes both sides and the lower soil, thereby forming a continuous sliding surface, standing There are obvious straight and spiral segments on the sliding surface. At this time, the Prandtl failure mode appears on the homogeneous foundation. At the same time, observing the upper surface of the foundation shows that the closer the edge of the loading area is to the center point of the loading area, the greater the shear movement rate. As the distance from the center point increases, the shear movement rate decreases.

Figure 4 (b) ~ (j) show the shear strain rate cloud diagram of the double-layer foundation when the replacement gravel cushion is 0.3 ~ 1.2m. It can be seen from the figure that the failure modes for heterogeneous foundations mainly include global shear failure and local shear failure. Which failure mode occurs depends on the thickness of the gravel cushion. When the gravel cushion is 0.3 and 0.4m, the failure mode of the foundation is shown in (c) and (d). It can be seen that the failure mode of the foundation is the overall shear failure, and the shape of the sliding surface on the front elevation Arc-shaped failure mode; when the gravel cushion is 0.5 ~ 1.0m, the foundation failure mode is shown in (d) ~ (i), it can be seen that the sliding surface of the foundation does not penetrate to the surface, and the depth direction enters the lower attachment Soft soil layer, showing local shear failure. This is because the shell effect of the hard soil layer is not obvious when the gravel cushion is between 0.5 and 1.0m, the stress diffusion range is small, and the stress concentration on the lower soft soil layer makes the plastic zone of the soil under external load It is concentrated under the loading area without forming a through sliding surface. At the same time, by observing the horizontal ground in (d) ~ (i), it can be found that with the increase of the thickness of the gravel cushion, the soil body participating in the shear failure of the foundation increases significantly in the horizontal range; when the gravel cushion When it is 1.2m, the foundation failure mode is shown in figure (j). From the figure, it can be seen that the foundation is sheared and destroyed overall, and the depth of the sliding surface is limited to the gravel cushion. There is no obvious active area under the loading area, and the sliding surface on the front elevation shows a clear Hill failure mode.

## 3. Summary

In this paper, the finite difference FLAC3D software is used to establish a three-dimensional foundation model of homogeneous and filled gravel cushions with different thicknesses, and the numerical simulation of the bearing capacity of homogeneous foundation and double-layer foundation under the uniform load of adjacent rectangles The ultimate bearing capacity of the foundation and the failure mode of the foundation are analyzed and compared. We get conclusion:

The double-layer foundation after replacing the gravel cushion has a significantly improved ultimate bearing capacity compared with the homogeneous foundation. When the gravel cushion is within a certain thickness, the thickness of the gravel cushion increases the ultimate bearing capacity of the foundation increases linearly; beyond this range, the ultimate bearing capacity of the foundation tends to be stable. The settlement of the foundation is improved compared to the homogeneous foundation. When the load is p = 300 KPa, the thickness of the gravel cushion is 0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, corresponding to the settlement The amount is 74mm, 61mm, 60mm, 59mm, 57mm, 55mm, 54mm, 53mm, 48mm, 43mm, and after replacing the gravel cushion, the settlement of the homogeneous foundation is reduced by 18 %, 19%, 22%, 23%, 26%, 27%, 28%, 35%, 42%.

The ps curve of the double-layer foundation after replacing the gravel cushion basically went through the compaction stage, shear stage and failure stage proposed by Gersevanov, but a "step" -shaped inversion appeared in the curve The phenomenon is because the composite foundation of the gravel cushion is a heterogeneous structure of gravel and soil, the deformation modulus is different, and a series of combined changes occur in the material under the load. Under the action of temporary plastic load, part of the crushed stone is squeezed into the soil, and the skeleton structure of the soil is rearranged and combined to facilitate stress diffusion. At the same time, the p-s curve reflects the rapid increase of strain, and then the soil foundation tends to be dense, the deformation decreases rapidly, and the curve becomes flat.

The failure modes of the double-layer foundation mainly include integral shear failure and local shear failure. When the thickness of the gravel cushion is small, the local shear failure occurs on the foundation. This is because when the gravel cushion is small, the hard soil layer The shell effect is not obvious, the stress diffusion range is small, and the stress concentration on the lower soft soil layer is concentrated, so that the plastic zone of the soil body under the external load is concentrated below the loading area without forming a continuous sliding surface; when the gravel cushion If the thickness exceeds a certain range, the whole foundation will undergo shear failure.

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