# FE–MODELLING OF BEHAVIOUR OF GRANULAR ANCHORS IN ROCK AND SOILS

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**Abstract:** The paper is concerned with granular anchors in rock and soils. Model tests and numerical calculations were performed. The effect of different parameters on the behaviour of anchors was investigated: anchor length, anchor diameter, initial density and mean grain diameter of the granular material, anchor roughness and stiffness of the borehole wall. The experiments were modelled with a finite element method and a polar hypoplastic constitutive relation. The relation can capture the salient properties of granular materials during shearing. A satisfactory agreement between experiments and numerical calculations was obtained. Advantages and limitations of granular anchors in rock and soils were outlined.

**Keywords:** anchor, finite element method, granular material, hypoplasticity, polar continuum

## 1. Introduction

Grout anchors, injections, nailing are the methods usually used to stabilise soil near old historical structures. They increase the bearing capacity and the stability of the structure. However, they do not satisfy very often the requirements for the preservation of monuments since they damage historical substances (mortar, stones, and soil). Moreover, the injections are difficult to control and the used water weakens the soil. In turn, usual anchorage needs sometimes an additional strengthening of the structure. At present, granular anchors become a novel technology for soil and rock stabilisation in the practice [5, 8, 13, 14]. They consist of a steel rod embedded in a borehole containing dense sand or dense gravel. The wall of the borehole acts as constraint for the volume increase of the granulate. During shearing, each dense granulate undergoes dilatancy (volume increase). Since dilatancy is constrained by the borehole wall, large shear and normal stresses are created inside the granular body. They can even reach values of some MPa [10]. As a result, the bearing capacity of granular anchors considerably increases and can be similar to this of grout anchors. Such large increase is only possible when the granular material is very dense and the borehole wall is stiff enough. The advantages of granular anchors as compared to usual cement anchors are:

— the method is easy, quick and cheap,
— the method is reversible,
— the load can be applied immediately after installation,
— the size of the foreign body inside the historical substance is small,
— the method is chemically neutral,
— the drainage of the neighbouring soil is provided.

In this paper, the technology of granular anchors in rock and granular soils is described. The most important parameters influencing their design are discussed on the basis of model tests and numerical calculations with a finite element method and a polar hypoplastic constitutive model.

## 2. Granular anchors in rock

The installation of granular anchors in rock is shown in Figure 1. First, a hole is drilled in rock and a steel or a glas fiber rod is inserted. The rod can include an end steel plate. Next, sand is blown into the borehole through a tube using air pressure. Afterwards, a plate with a nut is attached to the head of the anchor and the anchor is prestressed. When pulling out the anchor rod, the granulate in the borehole tends to increase its volume which is, however, constrained by the rock wall. Due to that, an immense wall friction force is created along the anchor shaft.

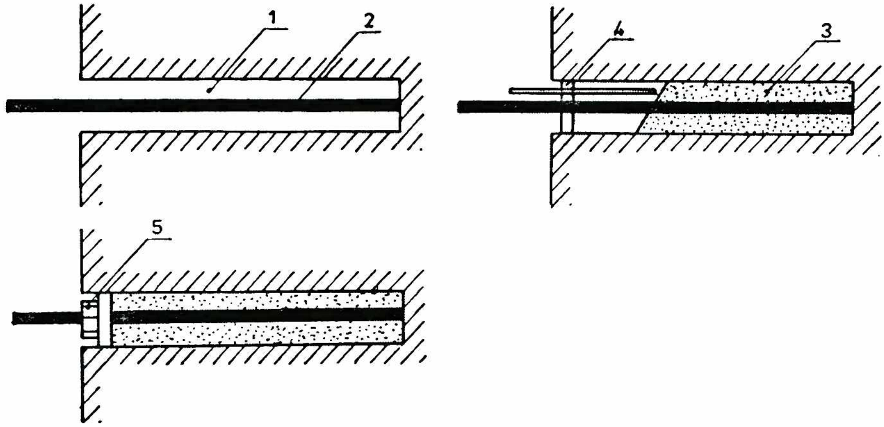


***Figure 1.*** *Construction of granular anchors in rock [14] (1. borehole, 2. steel rod, 3. dense sand, 4. head plate, 5. nut)*

To investigate the bearing capacity of granular anchors, model tests were carried out by J. Wehr at the Institute for Soil and Rock Mechanics of the Karlsruhe University [13, 14]. During experiments, the vertical force was measured which was needed to pull a vertical steel rod out of a borehole made the stiff rock and containing different granulates. The effect of the following parameters was studied: length $l$, diameter $d_r$ and wall roughness $r_w$ of the anchor rod, borehole diameter $d$, initial void ratio $e_o$ and mean grain diameter $d_{50}$ of granulates. The tests were performed with two rod diameters ($d_r$ = 15.4 mm and $d_r$ = 23.8 mm). The rod length was $l$ = 0.4 m and

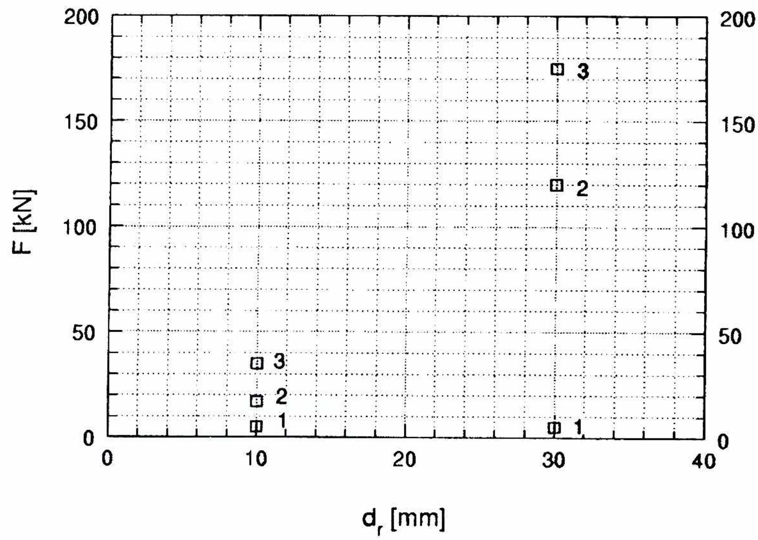


***Figure 2.*** *Pull-out force F versus the diameter of the steel anchor rod $d_r$ (1. smooth anchor rod, 2. screw-threaded anchor rod, 3. very rough anchor rod)*

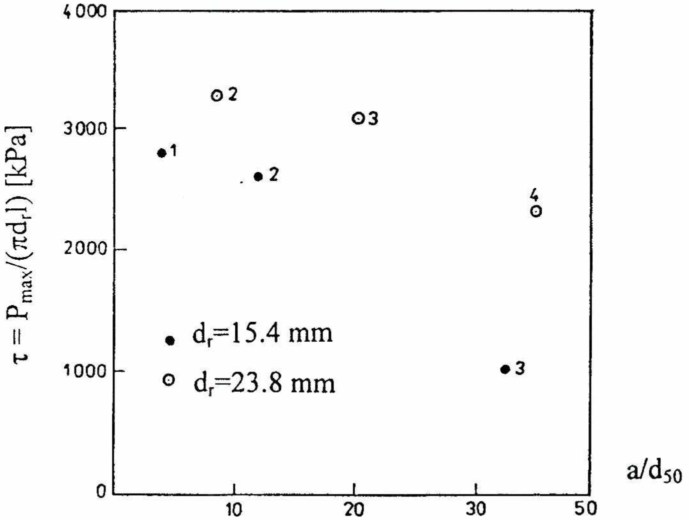


***Figure 3.*** *Mean shear stress τ along the shaft versus the ratio $a/d_{50}$ (1. fine gravel, 2. coarse sand, 3. medium sand, 4. fine sand). P – pull-out force, $d_r$ – rod diameter, l – rod length, a – width of the space between the rod and the borehole wall, $d_{50}$ – mean grain diameter*

the diameter of the borehole $d$= 37.7 mm. Figures 2 and 3 present some test results. Figure 2 shows the pull-out force versus the rod diameter for the different rod roughness. In Figure 3, the mean shear stress along the rod shaft is depicted versus the ratio between the width of the annular space between the rod and the borehole wall and the mean grain diameter using different granular materials.

The model tests revealed that the pull-out force increased with increasing rod roughness and mean grain diameter of the granulate, and decreasing initial void ratio of the granulate and the space width between the rod and the borehole wall. The optimum space width was found to be $4 \times d_{50}$. In addition, it was observed that dynamic effects in the form of continuous hammer blows in the neighbourhood of the anchor did not influence its bearing capacity. The effect of creep of granulates was insignificant as well.

## 3. Granular anchors in soils

The principle of the installation of granular anchors in soil is demonstrated in Figure 4. A borehole can be made by excavation or by pushing a drill tip. The

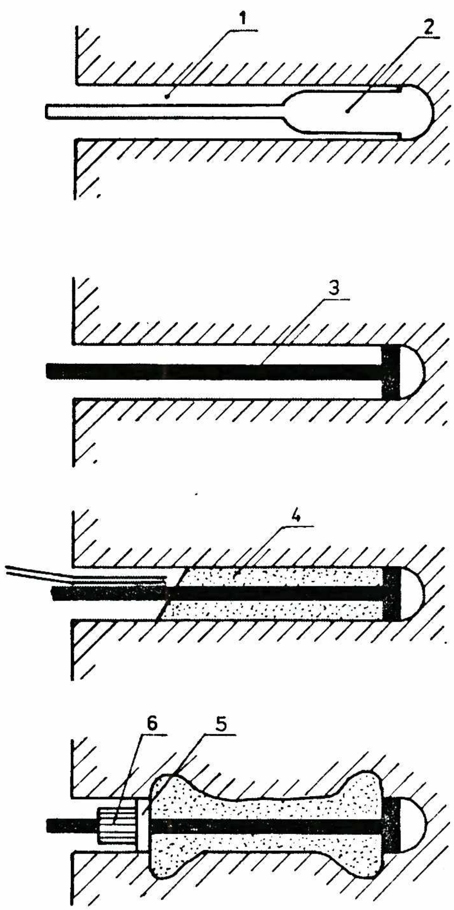


***Figure 4.*** *Installation of granular anchors in soils [14](1. borehole, 2. drill, 3. rod with an end plate, 4. dense granulate, 5. head plate, 6. nut)*

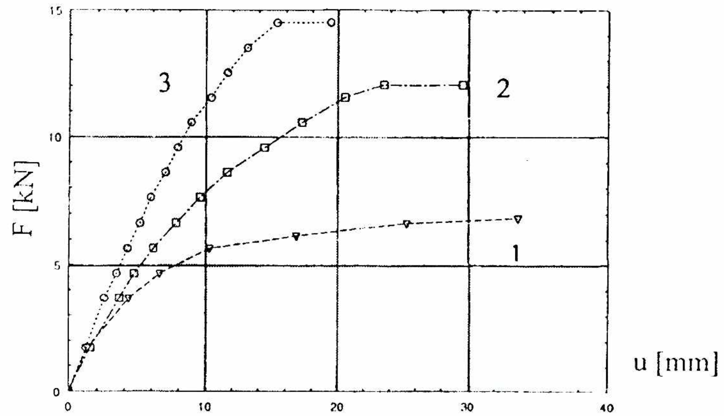


*Figure 5. Pull-out force F versus the anchor displacement u using a very rough anchor of $d_r$ = 24 mm and gravel of $d_{50}$ = 4 mm in silt: 1) l = 0.30 m, 2) l = 0.62 m, 3) l = 0.94 m*

anchor rod equipped with an end plate is inserted into the borehole. Next, the granulate is filled (*e.g.* through a special helical auger). Later, a plate with a nut is attached to the anchor head and the anchor is prestressed. The granular body becomes pear-shaped due to a decreased stiffness of the borehole wall. To estimate the bearing capacity of anchors in granular soils, vertical pull-out tests in slightly plastic silt were performed using gravel anchors.

Figure 5 presents the results of model tests for gravel anchors in silt using a very rough rod with a different length *l*. The borehole diameter was *d* = 80 mm, the space width between the rod and the soil a = 28 mm, and the mean grain diameter of fine gravel $d_{50}$ = 4 mm. The results show that the maximum pull-out force is about 10–20 times smaller in silt than in rock due to a decreased stiffness of the borehole wall. The maximum pull-out force is roughly proportional to the anchor length. The influence of dynamic effects (hammer blows) and gravel creep on the bearing capacity of anchors was insignificant.

## 4. Numerical calculations

The behaviour of granular anchors was analysed with a finite element method taking into account a polar hypoplastic constitutive law. This law was obtained by extension of a non-polar hypoplastic law according to Gudehus [6] and Bauer [1] to model the kinematics and thickness of shear zones in granular materials [9–12].

First, comprehensive numerical studies were carried out with sand anchors in rock during pulling out using so-called dry Karlsruhe sand ($d_{50}$ = 0.5 mm). The FE–calculations were performed for plane strain (Figure 6) and for an axisymmetric case (Figure 7). Large deformations and curvatures were taken into account. The length of the anchor rod was assumed to be *l* = 0.10 m and the width between the rod and the borehole wall *a* = 10 mm. The calculations were carried out with different initial void ratios, mean grain diameters, rod roughness and borehole stiffness. The wall

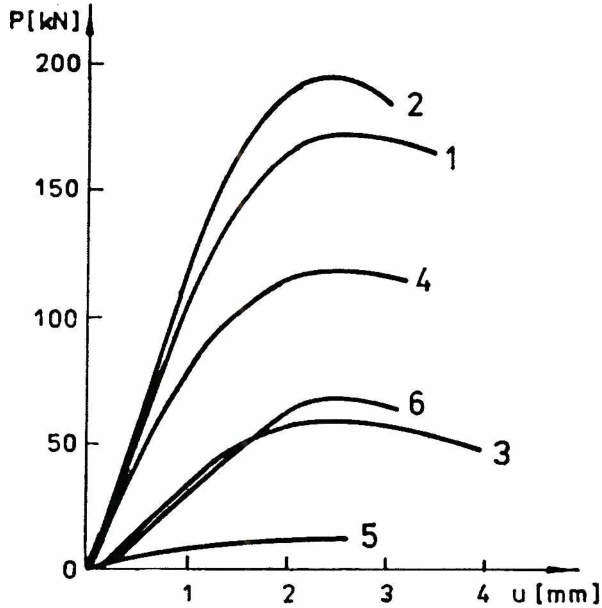


***Figure 6.*** *Numerical results for sand anchors in rock (plane strain): pull-out force P against the vertical anchor displacement u: 1)* $r_w = d_{50}$, $d_{50} = 0.5$ *mm,* $e_0 = 0.6$, $k = \infty$, *2)* $r_w = d_{50}$, $d_{50} = 0.75$ *mm,* $e_0 = 0.6$, $k = \infty$, *3)* $r_w = d_{50}$, $d_{50} = 0.5$ *mm,* $e_0 = 0.65$, $k = \infty$, *4)* $r_w = d_{50}$, $d_{50} = 0.5$ *mm,* $e_0 = 0.6$, $k = 10000$ *kN/m, 5)* $r_w = d_{50}$, $d_{50} = 0.5$ *mm,* $e_o = 0.6$, $k = 100$ *kN/m, 6)* $r_w = d_{50}/10$, $d_{50} = 0.5$ *mm,* $e_o = 0.6$, $k = \infty$

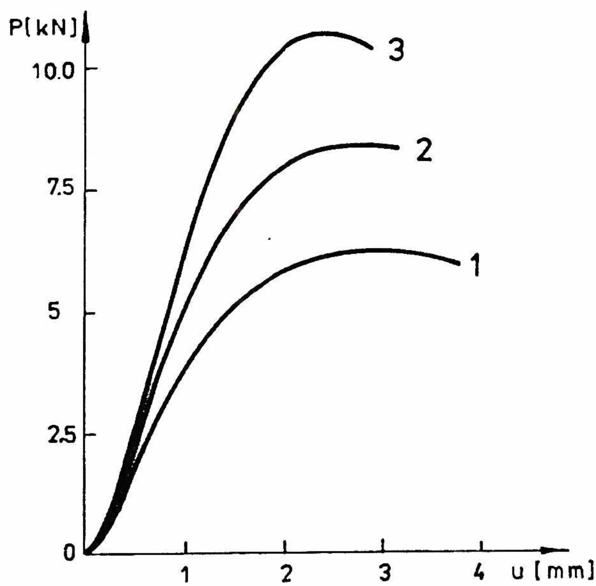


***Figure 7.*** *Numerical results for sand anchors in rock (axisymmetric case): pull-out force P against the vertical anchor displacement u (*$r_w = d_{50}$, $e_o = 0.6$, $k = \infty$*): 1)* $d_{50} = 0.5$ *mm,* $d_r = 15.4$ *mm, 2)* $d_{50} = 0.5$ *mm,* $d_r = 23.8$ *mm, 3)* $d_{50} = 1.0$ *mm,* $d_r = 23.8$ *mm*

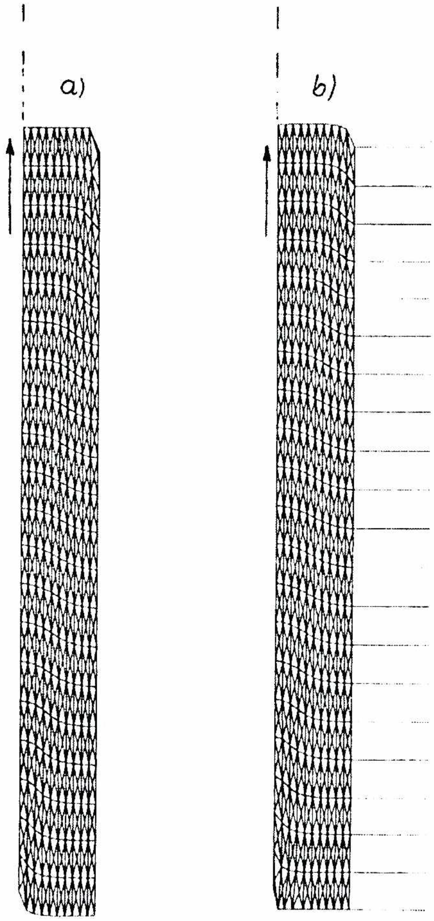


*Figure 8. Deformed FE-meshes (plane strain, $d_{50}$= 0.5 mm, $e_0$= 0.60): a) $k = \infty$, b) $k$ = 10000 kN/m*

stiffness was simulated by means of horizontal springs of varied stiffness $k$. To model a very rough surface of the rod ($r_w \geq d_{50}$), full shearing of the granulate was assumed ($u_1 = 0$, $u_2 = 0$, $\omega^c = 0$). To simulate a rough surface ($r_w < d_{50}$), the following assumptions were made along the shaft: $u_1 = 0$, $\omega^c/u_2 = r_w/d_{50}^2$ ($r_w = d_{50}/10$). $u_1$ denotes the horizontal displacement, $u_2$ – vertical displacement, $\omega^c$– Cosserat rotation $r_w$ – wall roughness, $d_{50}$ – mean grain diameter.

The numerical results (Figures 6–8) are qualitatively in agreement with experiments. The bearing capacity of anchors increases with increasing initial void ratio of sand, mean grain diameter of sand, rod roughness and borehole wall stiffness. Along the shaft of the anchor rod, shear zone is created with thickness equal to the width of the space between the rod and the wall (Figure 8). In the wall shear zone, Cosserat rotations and couple stresses are noticeable. The mean shear stress is 2.5 times smaller than in the experiment (Figure 3) due to other properties of the sand used.

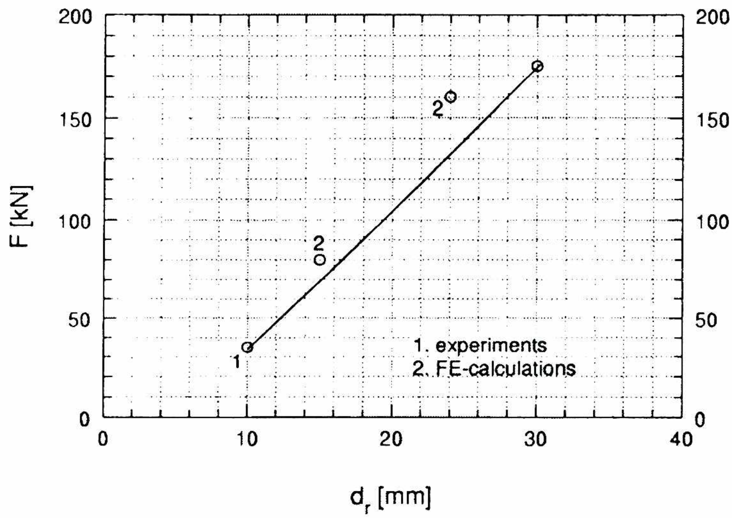


***Figure 9.*** *Calculated maximum pull-out force F against the diameter of the anchor rod $d_r$ for fine gravel in rock ($d_{50}$ = 2.8 mm, d = 37.7 mm)*

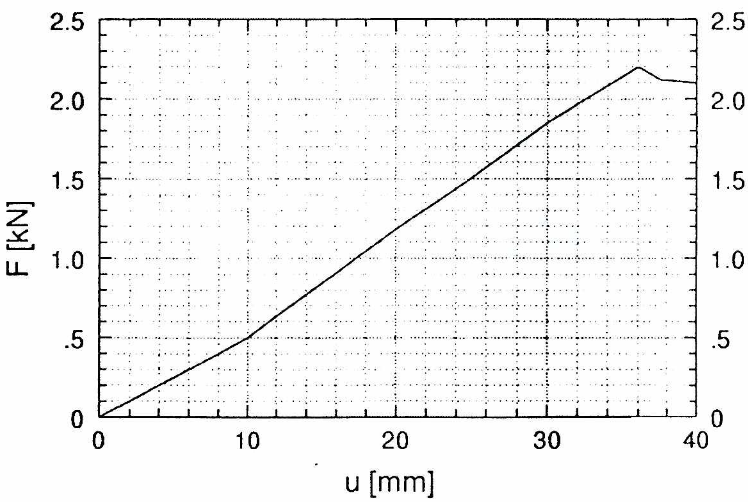


***Figure 10.*** *Calculated pull-out force F against the vertical displacement of the anchor rod u for gravel in silt ($d_{50}$ = 4 mm, l = 0.3 m, $d_r$ = 24 mm, d = 80 mm)*

Next, some experiments with gravel anchors in rock were numerically simulated. Figure 9 demonstrates the comparison between the calculated pull-out forces. The FE–results agree very well with the experimental values.

Figure 10 shows the numerical result for gravel anchors in silt. The calculated maximum pull-out force, $F = 2.3$ kN, is about three times lower than the measured one of 6.8 kN (curve 1 in Figure 5). The reason is that the process of the borehole realisation in the soil (which causes the densification and stiffness increase of the neighbouring soil) was not modelled. Due to that the calculated force $F$ was smaller. To obtain a better agreement with the experiment, the process of the borehole performing has to be taken into account [14].

## 5. Conclusions

Granular anchors are an alternative to traditional methods for soil stabilisation, in particular near historical structures. They have several advantages such as: short time of installation, fast application of the load, reversibility, chemical neutrality, soil drainage, low costs and slight disturbance of the historical substance.

The bearing capacity of granular anchors increases with an increase of the initial density of the granulate, the mean grain diameter, rod roughness and the borehole wall stiffness, and a decrease of the space width between the anchor rod and the borehole wall.

A polar hypoplastic constitutive model can realistically describe the behaviour of granular anchors. It takes into account the influence of the density, the pressure level, the deformation direction and the mean grain diameter on the behaviour of granular materials. Numerical results do not depend on the FE–mesh size due to the presence of the characteristic length.

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