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THE SIZE EFFECT OF ROCK SAMPLE USED IN ANCHORAGE PERFORMANCE TESTING OF CABLE BOLTS

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ABSTRACT: This paper outlines the results of a study into the effect of rock specimen size on the anchorage performance of a hollow strand bulbed cable bolt. As part of the design of a Laboratory Short Encapsulation Pull Test (LSEPT) facility, a question arose as to the appropriate size of the rock sample in which the cable bolt is embedded and whether size might affect the pull out strength of the cable bolt. An analysis of previous research revealed little information regarding the rationale for the sample size used in previous test work. Many of pull out tests in the past had made use of either a rigid encasment such as steel, aluminium, or PVC casing or a biaxial pressure cell to apply a constant stress to model the *in situ* rock mass conditions.

A test arrangement was developed to assess whether there was any appreciable change in anchorage performance with varying diameter of the rock sample. Cable bolts were embedded into the rock sample using a polyester resin grout having diameters of 150 mm, 215 mm, 300 mm and 450 mm with a constant embedment length of 280 mm. A hollow hydraulic ram was used to load the cable bolts to failure.

The results indicate there was a size effect albeit only marginal whereby an increase in the diameter resulted in increased anchorage capacity of the cable bolt.

INTRODUCTION

Cable bolting is widely utilised in ground support of surface and underground excavations in both mining and civil engineering applications. Since they were first used in the 1970s, a wide variety of cable bolt configurations and geometries have been developed. The performance of cable bolts has been found to be is affected by parameters that include:

- borehole diameter;
- embedment length;
- borehole radial confinement conditions;
- cable bolt configurations and geometry; and
- grout type and quality (Hutchinson and Diederichs, 1996).

The failure mechanism of cable bolting systems is complex and a function of loading conditions and the interaction between the cable bolt, grout and rock mass. There are four general mechanisms of cable bolt failure each of which is illustrated in Figure 1.

Failure at the cable-grout interface, indicated as Mode (ii) in Figure 1, is considered the most common failure mechanism identified in the field (Hyett, *et al*., 1996; Hyett, *et al.*, 1995; Hutchinson and Diederichs, 1996; Rajaie, 1990; Singh, *et al.*, 2001). This usually results from insufficient frictional resistance between the ridges on the cable strands and the grout material. A combination of poor ground conditions and lack of quality control at the time of installation may also affect the bond strengths at the interfaces that in turn can lead to premature failure of the system before the capacity of the cable bolt is actually achieved. Hence a standardised testing methodology should be designed such that failure of the system is more likely to occur at the cable-grout interface (Rajaie, 1990; Hutchinson and Diederichs, 1996).

A comprehensive review of the testing methodologies revealed that while there are a number of testing methods that have the potential to become the standard for pull out tests, there is no standardised or universally accepted suggested method with which to assess the strength of the wide range of cable

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bolts that are available to industry. Essentially there are two approaches that have been adopted in the past in the design of a testing facility these being either a constant stiffness system where the material in which the cable bolt is embedded is encased in a steel of other rigid tube or pipe such as the double-embedment test or, a constant load system where the material is placed within a pressurised biaxial cell.

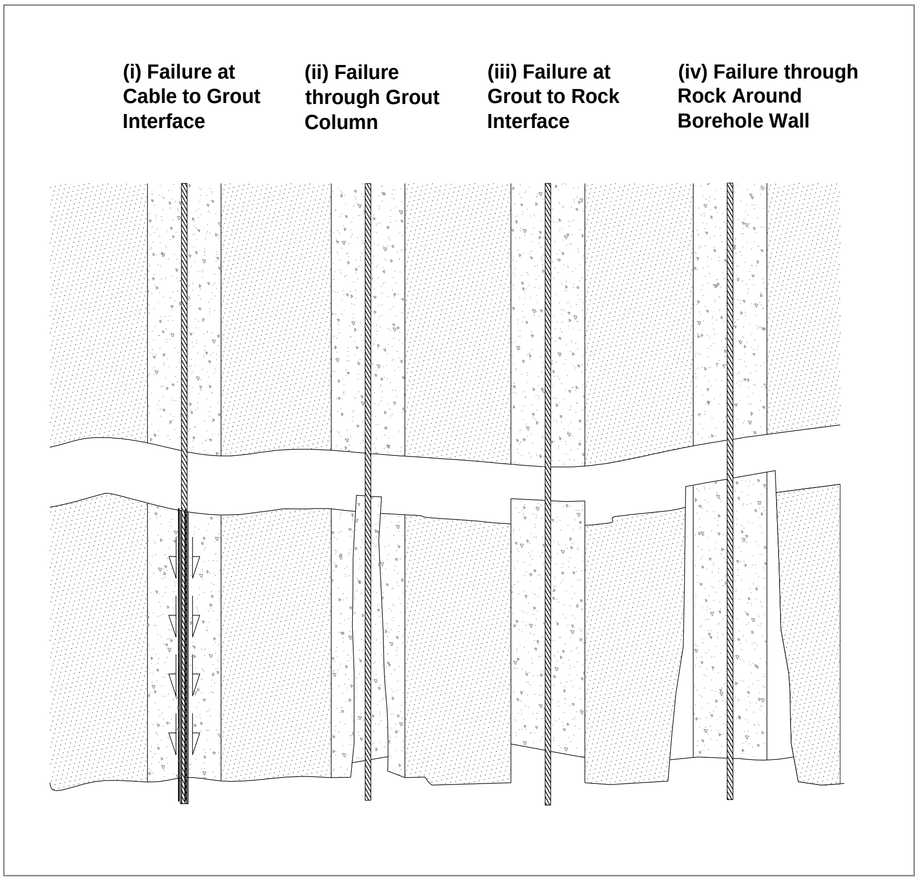

Figure 1 - Schematic illustration of the four modes of load transfer related failure in cable bolts (Thomas, 2012)

Following a recent analysis of various pull out testing arrangements it was concluded the Laboratory Short Encapsulation Pull Test (LSEPT) as developed by Clifford *et al.* (2001) and reported by Thomas (2012) is the most appropriate method to test the extensive range of cable bolts available. One of the key advantages of the LSEPT is that one end of thecable bolt is embedded in a cylinder of material as can be seen in Figure 2. In other tests the cable bolt is embedded in a rigid or semi-rigid casing such as a steel tube in the double embedment test which acts to constrain any lateral dilation. On axial loading, cable bolts activate some level of lateral dilation stress in a rock mass as part of the load transfer process which can influence the magnitude and distribution of stress within the rock mass. The level of this dilation varies with the different cable bolt designs. There is little published information however about the size effects of the material cylinder at the cable bolt/grout, grout/rock and rock containment interfaces during testing and consequently on the load/deformation characteristics and ultimate load achieved by the cable bolt. Hence in developing a standard test method it is important to determine the minimum size of cylindrical block that will not affect the anchorage performance of a cable bolt.

A study by Rajaie (1990) reported a link between the anchorage strength of a cable bolt and the diameter of the rock sample surrounding the grouted cable bolt. It was found that there was little change in load carrying capacity of the cable bolt with a specimen diameter in excess of 250 mm as can be seen Figure 3. This study however only involved a plain strand cable bolt that was in common use at that time. It therefore needs to be confirmed whether the same limit applies to the modified cable bolts now available such as bulbed and birdcage bolts. The newer type cable bolts are likely to induce higher lateral stresses during failure requiring a larger rock mass to deal with the dilation generated by the bolt.

In the design of a standardised pull-out test, the diameter of the rock specimen should be such as to withstand the range of stresses generated by the range of modified geometry cable bolt designs. This diameter should remain within practical limits to enable ease in logistics and sourcing such a rock sample, as well as, for compatibility with testing equipment.

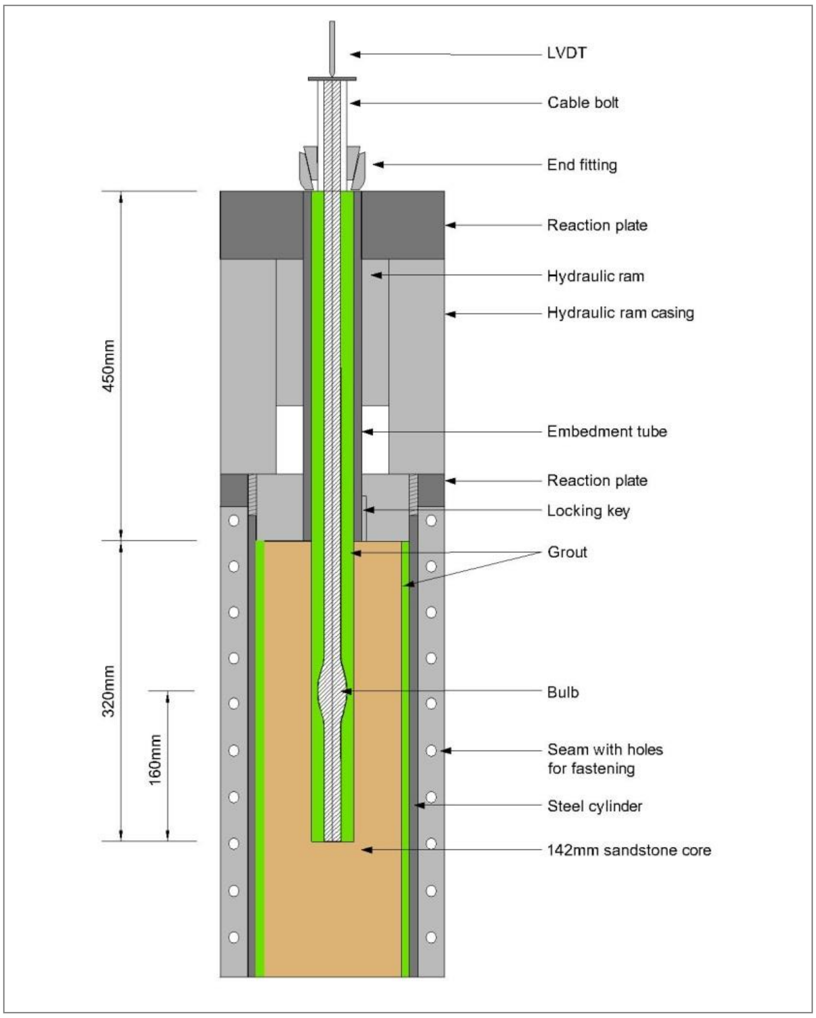

Figure 2 - Modified version of the laboratory short encapsulation pull test incorporating a steel cylinder (Thomas, 2012)

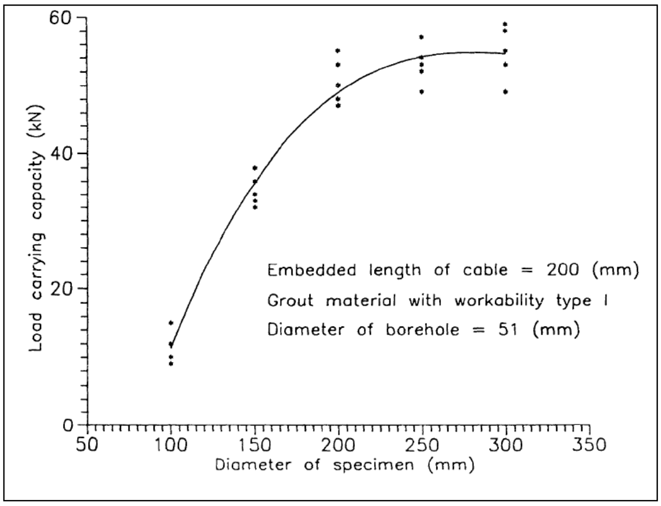

Figure 3 - Load carrying capacity for different external diameter sample (Rajaie, 1990)

EXPERIMENTAL PROCEDURE

Test specimen preparation

A total of 16 artificial rock cylinders were prepared, each 300 mm in length and having diameters of 150 mm, 215 mm, 300 mm and 450 mm. A 35 mm TG bolt was embedded in a 38 mm diameter hole with the centre of the bulb located close to the midpoint of the cylinder, at a constant distance of 140 mm from the cylinder end as shown in Figure 4.

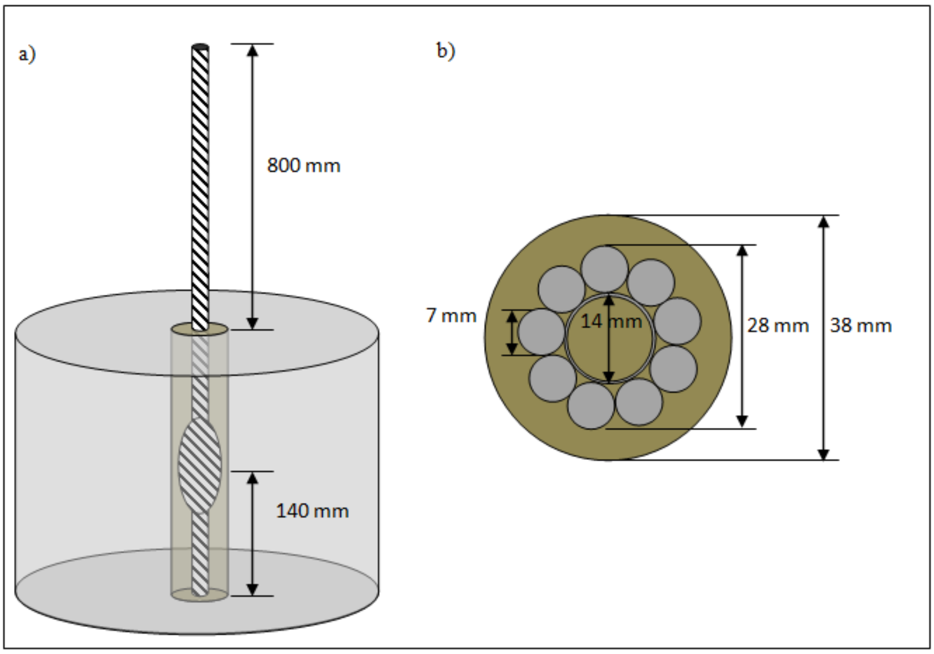

Figure 4 - a) Schematic of cable bolt installation technique; b) Cross-section of resin column and cable bolt

Each test specimen was formed using the following four step process:

Step 1 - Rock samples were cast in moulds made from thick-walled cardboard cylinders of the desired diameter size: 150 mm, 215 mm, 300 mm and 450 mm. Water was added to super strength grout and mixed to a water to cement ratio of 0.3 and then poured into the moulds to a height of approximately 300 mm. Vibration of the samples occurred post-pouring to remove excess air bubbles entrained in the grout during the mixing process, to create a stronger homogeneous material. The cardboard cylinders were lined with casting oil prior to pouring the grout mixture to minimise water seepage that could create shrinkage cracking along the sides of the sample. The oil also allowed for ease in removing the rock cylinders from the mould after curing.

Step 2 - The samples were left to cure for two weeks. Boreholes were then drilled with a diamond core drill to create a 38 mm hole, in accordance with the manufacturer's specification (Jennmar, 2010). This produced relatively smooth side walls compared with field drilling techniques which create hole rifling and roughened walls. Ideally the boreholes should be drilled using a twin wing or finger bit creating a hole rifling effect. Attempts were made post drilling to mimic hole rifling conditions and roughen the wall surface of one of the 300 mm diameter samples, however no consistent method of creating such conditions was achieved. As a result, all the holes were left untreated for the pull out tests.

Step 3 - The cable bolts were grouted into each rock cylinder using a slow set resin with a setting time of 20 to 25 minutes. The resin and oil based catalyst were mixed for 13 minutes. An electric mixer was employed to combine the two components to ensure a thorough and even distribution of catalyst throughout the resin, which is imperative for the ultimate strength of the cured resin. The mixed resin was poured into the boreholes to a height 50 mm below the top of the borehole. This allowed room for displacement of the resin after the cable bolt was installed into the borehole. Excess resin spilled out around the rim of the borehole.

Step 4 - Immediately following pouring of the resin into the hole, the cable bolt was spun, by hand, into the borehole to ensure complete encapsulation of the bolt, and particularly to infuse the bulb and hollow strand with resin. To ensure centrality of the bolt in the borehole and to maintain a constant embedment length of 280 mm, with the bulb located 140 mm from the top of the borehole, a simple frame was attached to the bolt using L-shaped brackets. Later examination of the samples showed the low viscosity of the resin enabled it to penetrate inside the bulb of the cable bolt as well as the central hollow strand. A cross-sectional schematic of the 5 mm thick resin annulus surrounding the bolt can be seen in Figure 4b. The final specimen with embedded cable bolt can be seen in Figure 4a, with the free end of the cable bolt extending 800 mm from the face of the rock cylinder to enable sufficient length to be secured by the loading machine.

Pull out test arrangement

The cable bolt in each cylindrical sample was axially loaded to failure to determine the failure characteristics and anchorage capacity. The equipment arrangement used in each test is shown in Figure 5.

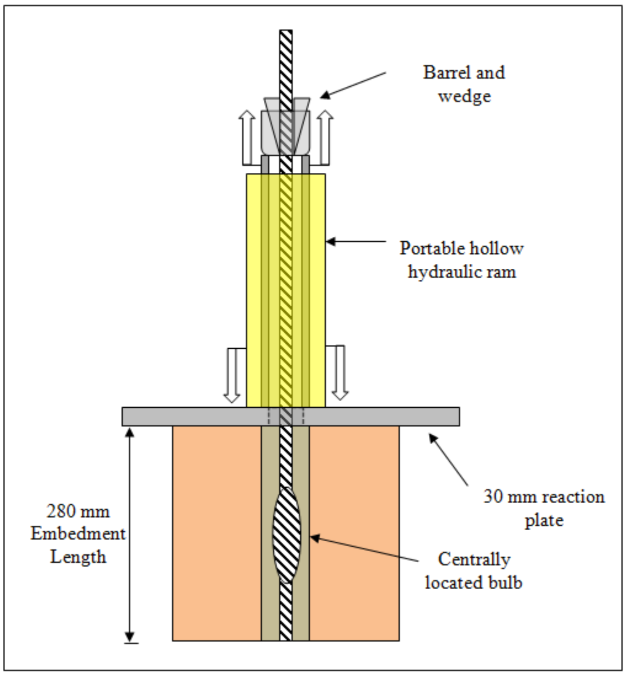

Figure 5 - Schematic of pull testing arrangement using hydraulic cylinder

The test arrangement employed a 600 kN capacity RCH606 hollow hydraulic cylinder to load the cable bolt specimen. One end of the cylinder acted against a barrel and wedge attached to the free end of the cable bolt while the other end reacted against a plate placed on top of the cylindrical sample as shown in Figure 5.

This loading arrangement is similar to the setup designed by Ito *et al.* (2001). The displacement of the cable bolts under load was measured using a Linear Variable Differential Transformer (LVDT) attached to the outer casing of the hydraulic cylinder, while the axial load was measured using a pressure transducer attached to the hydraulic pump.

EXPERIMENTAL RESULTS

Results from the pull outs tests are summarised in Table 1 showing the maximum load recorded for each cylinder diameter.
The results fall into one of two categories of failure:

- Type 1 failure that occurs at the grout/rock interface; and
- Type 2 failure that occurs at the bolt/grout interface.

The majority of the samples failed at the grout/rock interface with only three specimens failing at the cable bolt/grout interface as indicated in Table 1. Also identified in the table is one 300 mm sample which had a roughened borehole wall as a result of rifling the borehole post-coring.

The 13 specimens that failed at the rock-grout boundary showed detachment between the grout column and the borehole walls, which was clearly visible during later examination of the test samples. Despite this debonding between the resin column and the cylindrical sample, high loads were attained before failure occurred.

Table 1 - Summary of pull out loads for TG bolts embedded in cylindrical block samples (All samples failed at grout/rock interface unless otherwise indicated)

Cylinder diameter (mm)	Peak Load (kN)				
	Test Number				mean ± s.d.
	1	2	3	4	
150	55	-	107*	109*	90.3 ± 30.6
215	45	116	56	46	65.8 ± 33.9
300	61	58	125**	86	82.5 ± 31.0
450	61	131	142*	165	124.8 ± 44.8

* Sample failed along the bolt/grout interface; ** Roughened borehole wall

Figure 6 shows a graph of the ultimate pull out load against rock cylinder diameter. Over the range of diameters examined there is an increasing relationship in the load capacity of the cable bolts with diameter. This would suggest that the range of diameters tested was not sufficient for a limiting relationship to become apparent.

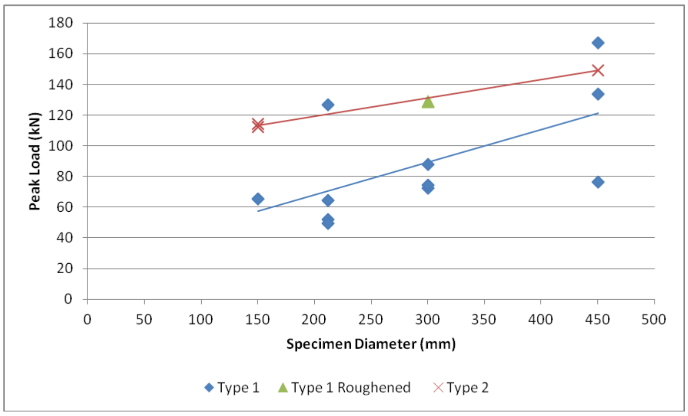

Figure 6 - Variation in peak load with cylinder diameter

INTERPRETATION OF EXPERIMENTAL RESULTS

Initial interpretation of the results from the pull out tests suggests the forces were within the predicted loading range and the load versus displacement relationships were consistent with previous pull out test results (Thomas, 2012; Rajaie, 1990; Hyett, *et al.*, 1996). Subsequent analysis of the measured results together with observational evidence indicates there may have been other contributing factors. Inspection of the relatively intact resin-grout column and smooth borehole walls of the 13 samples that failed at the rock/grout interface suggest these samples should have failed at lower loads.

However, this was not the case as the measured loads were markedly higher for the larger diameter samples which reached loads in excess of 150 kN when compared to 60 kN with the smaller diameters. If bolt/grout failure had occurred as opposed to the weaker rock-grout failure, this relationship would have been valid.

The radial tension cracking that developed in all of the samples suggest there is some form of dilation in the system, stressing the sidewalls of the borehole, examples of which can be seen in Figure 7. This seems to contradict the lack of evidence for dilation, with the relatively smooth condition of the borehole, the intact resin column and minimal cable bolt displacement suggesting otherwise. All this suggests that the shear forces at the artificial rock-grout interface could not have generated the level of stresses necessary to fracture the samples.

Figure 7 - Evidence of radial tension cracking across all rock cylinder diameters

Further analysis of these findings revealed two possible mechanisms that might be responsible for the inconsistency between the observed peak failure loads as well as the apparent contradiction of observed radial tension cracking and the lack of evidence for radial dilation:

1. The resin-grout column slowly failed along the smooth rock-grout interface, requiring relatively low loads to overcome shear resistance along this boundary. However, the grout column's movement is constrained by the small size of hole in the steel reaction or bearing plate placed between the top of the cylinder and hydraulic ram, this being smaller than the diameter of the borehole.

   This resulted in the grout being compressed causing dilation of the grout due to the Poisson effect and thereby increasing the radial stress in the surrounding rock. This caused the sample to fail in a manner similar to the pull out tests revealed in previous research through radial tension cracking (Rajaie, 1990; Ito, *et al.*, 2001). A schematic of arrangement is illustrated in Figure 8.

2. The resin grout column failed in a similar manner described in 1) however the induced stressed in the surrounding rock are generated by moment forces being transferred through the grout column.

   Eccentric loading conditions at the point of contact between the hole in the steel plate and the grout annulus are generated by slight misalignment of the resin column and the hole.

   This results in moment forces acting on the borehole walls as the grout column pivots around the steel plate contact point on the edge of the hole. This is illustrated in Figure 9.

CONCLUSIONS

The single embedment length unconstrained pull out tests found a slight increase in cable bolt anchorage capacity with size of the cylindrical block sample containing the cable bolt.

In three tests where there was failure at the cable bolt/grout interface, which included two 150 mm diameter specimens and one 450 mm sample, anchorage capacity of the cable bolt increased with diameter of the cylinder used in the tests. The peak load achieved with the two smaller diameter cylinders was approximately 110 kN while the larger cylinder achieved a peak load of 140 kN.

Of the remaining tests, 13 samples failed along the rock/grout interface. It is unlikely that the failure mechanisms in this instance is representative of the expected *in situ* failure conditions due in part to the relatively smooth surface of the borehole and confinement of the grout caused by the steel loading plate during loading.

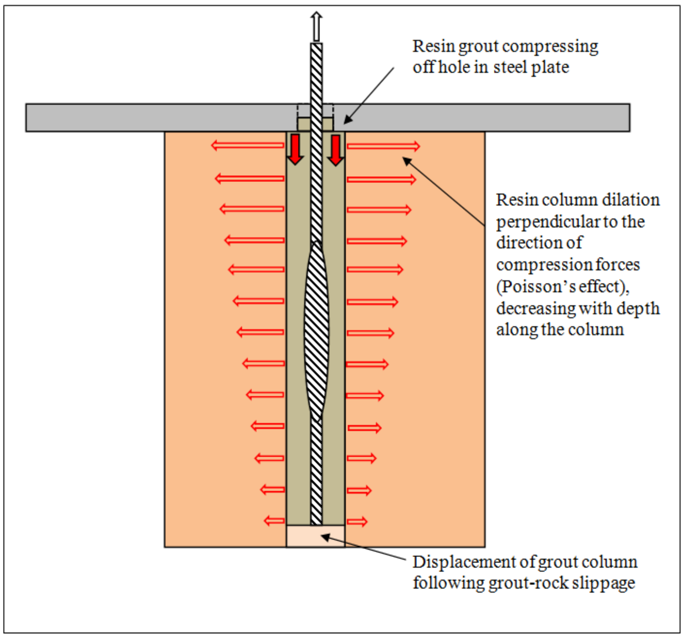

Figure 8 - Schematic of resin column dilation inducing sample failure

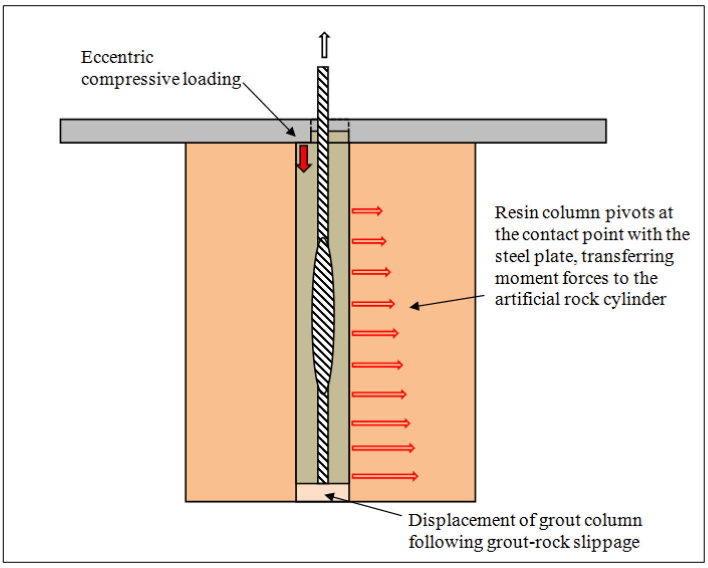

Figure 9 - Schematic of eccentric loading failure mechanism

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