Numerical analysis of undercut anchor effect on rock

J Jonak, R Karpiński and A Wójcik

Lublin University of Technology, Faculty of Mechanical Engineering, Department of Machine Design and Mechatronics, Nadbystrzycka 36, 20-618 Lublin, Poland.

j.jonak@pollub.pl, r.karpinski@pollub.pl

Abstract. The paper presents the results of a numerical analysis using the Finite Element Method (FEM) of the friction issue in the contact between the undercut anchor head and rock during anchor pull-out. Formation of failure zone of rock medium was analysed assuming different Coulomb friction coefficients in the contact zone of conical anchor head with a rock. The problem is interesting as regards practical aspects of rock mass loosening during anchor pull-out. The analysis revealed a significant effect of the friction coefficient on the propagation and extent of the failure zone. Increasing the friction factor significantly decreases the extent of the failure zone measured on a free rock surface.

1. Introduction

The use of numerical modelling in combination with the results obtained from experimental studies enabled a detailed understanding of the actual behaviour of engineering structures and their optimisation [1–6]. The issue related to the estimation of load capacity of anchors typically used in the installation of equipment, in concrete engineering structures is topical and constantly developed due to its importance in strategic facilities such as nuclear power plants and other constructions located in the earthquake zone [7–9]. To date, several empirical models have been developed to describe the mechanism of cone failure formation in concrete under the action of anchors of common designs and installation technologies [10–16]. The main focus has been on determining the minimum pull-out force of an anchor given its intended load-carrying capacity (load capacity) [17–20]. Using neural networks, the load capacity of anchors is predicted (e.g. [10]) and using FEM (Finite Element Method) systems, models are built to predict the propagation of failure of the medium under the action of the anchor, to estimate its load capacity depending on the structural parameters of the anchor or anchor installation technology [21–23]. The authors of this paper try to apply the technology of installing undercut anchors and then pulling them out (along with the resulting cone failure), to potential rock loosening in unusual conditions of mining works. An example of such can be tunnelling during rescue operations in collapsed galleries when there is an increased concentration of methane and a risk of explosion. Another potential application can be the modernisation of engineering structures, where mining with explosives cannot be performed, or mining with mechanised systems. The subject of the study concerns the technology of loosening potentially large rock fragments with the use of undercut anchors (Figure 1) [7].

From the point of view of the proposed loosening technology, for a given depth of embedment, it is important to obtain the maximum range of loosening. This translates into the volumes of the detached solids, which in turn affects the overall evaluation of the efficiency of the process. In the light of existing knowledge, undercut anchors are generally used for equipment installation technology in engineered concrete structures [24–26]. The failure zone of concrete is roughly described, among other things, as a
cone of the height of $h_{ef}$ and base diameter of $3h_{ef}$ (measured on the free surface of the concrete), e.g. [25,27,28], as in Figure 2.

For sandstones, it has been found [29,30] that the extent of the failure zone is much larger than in the case of concretes. Numerical analyses of the formation of the failure zone under the action of a single anchor [31], two anchors [32] and an assembly of three anchors [33] have been carried out. In the case of an anchor assembly [32,33], the interaction effect of “cone failure” that then appears, depending on the anchor spacing, has been analysed more closely. For the same embedment depth and the same anchor pull-out force, this effect can lead to an increase in the volume of the loosened elements (with a suitably chosen anchor spacing).

![HILTI Anchor: a) Anchor before installation, b) Anchor head after installation, $\beta$ – the angle of undercut head after installation in the mounting hole.](image1)

Figure 1. HILTI Anchor: a) Anchor before installation, b) Anchor head after installation, $\beta$ – the angle of undercut head after installation in the mounting hole.

![Substitute failure zone model as a so-called “breakout cone”: $h_{ef}$ – Effective embedment depth, $\alpha$ – the angle of cone failure.](image2)

Figure 2. Substitute failure zone model as a so-called “breakout cone”: $h_{ef}$ – Effective embedment depth, $\alpha$ – the angle of cone failure.

The extent and course of the failure zone depend on a plethora of factors. In addition to the effective embedment depth $h_{ef}$, they depend on the physical and mechanical parameters of the rock (e.g. Young’s modulus, Poisson’s ratio, tensile strength) [34], the value of the angle of the undercut head $\beta$ [35,36] and the value of the friction coefficient in the contact of the head with a rock.
The effect of the friction coefficient on the formation of the cone failure angle $\alpha$ in the initial stage of failure zone development is of particular interest in this study.

2. FEM simulation using ABAQUS

The action of the $i$-th undercut element of the anchor head on the rock (Figure 1) can be considered as a typical contact issue with friction. As a result of the force $F$, there is a visible deformation in the rock structure and relative movement of the rock along the surface of the conical part of the head with the angle of the cone $\beta$. $F_i$ component of $F$ per undercut element can therefore be decomposed into a normal force ($F_n$) to the conical surface and the longitudinal (friction) component $F_f$. As a result, the $i$-th undercut element acts on the rock with a resultant force $F_r$, at an angle $\varepsilon$ concerning the axis $X$ of the adopted coordinate system. This angle is the sum of the angle of friction $\rho$ of rock against the head and the angle of the head $\beta$ (i.e., $\varepsilon=\rho+\beta$). It should also be noted that the action of the horizontal component $F_x$ will translate into the size of rock deformation in the direction of the axis $X$.

Assuming a constant value for the effective embedment depth $h_{ef}$ and a constant head angle value $\beta$, using FEM ABAQUS (Abaqus 2019, Dassault Systems Simulia Corporation, Velizy Villacoublay, France) the formation of the rock failure zone was analysed, in particular the propagation angle $\alpha$ of the failure/crack surface at the initial stage of failure development.

The problem was considered axisymmetric. The analysis used a finite element mesh discretised model as in Figure 4a. The mesh was compacted along the potential failure surface, inclined at an angle $\alpha$ to axis X (approx. 25°, e.g. [31]). The method of restraining the boundary nodes of the model is illustrated in Figure 4b. Forcing in the form of controlled displacement of the anchor along its axis (along the Y-axis of the adopted coordinate system) was applied.
Figure 4. Method of discretisation of the model with the finite element mesh (a) and forcing and restraint of model nodes, l – length of the rock contact zone with the conical part of the undercut head, U1=U2=UR3=0, u1-u2-ur3 nodes with displacements in X and Y directions and rotation about Z-axis (perpendicular), u1 - nodes with displacement in X-axis direction.

Only for this analysis, the friction coefficient value $\mu = 0.0, 0.015, 0.25, 0.75, 1.0, 1.5$ was used in the simulation. The actual value of the contact friction coefficient depends on several factors, i.e., rock grain size, type of grain bonding medium, rock moisture content, type of anchor material, etc. According to various literature sources, it may vary from 0.2 to 0.4. Embedment depth was assumed to be $h_e=80\text{mm}$.

Finite elements were used:
- **Sandstone**: Element type: CAX4R: A 4-node bilinear axisymmetric quadrilateral, reduced integration, hourglass control.
- **Anchor**: Element type: CAX4R.

Assumptions for simulation:
- Type of material:
  - Sandstone: Elastic, Isotropic, Quasi-Brittle materials. Elastic Modulus – $E = 14276 \text{ MPa}$, Poisson’s ratio – $\nu = 0.247$, Tensile Strength – $\sigma_t = 7.74 \text{ MPa}$,
  - Steel – material: Elastic, Isotropic, Elastic Modulus – $E = 210000 \text{ MPa}$, Poisson’s Ratio – $\nu = 0.3$.
- **Damage initiation** in rock material: Maximal Principal Stress,
**Damage evolution**: type: Energy, Softening: Linear. Damage for traction separation Laws: Maximal Principal Stress Damage, Fracture Energy = 0.355 N/mm.

The interaction of the anchor with the rock was treated as a contact issue, with Coulomb friction. Interaction between rock and anchor: – Interaction Type: Surface-To-Surface Contact (Standard), Discretisation method: Surface to surface. Finite sliding. The simulation results are shown in Figure 5.

**Figure 5.** Effect of contact friction coefficient on the course and extent of the rock failure trajectory:
- a) $\mu = 0.0$
- b) $\mu = 0.015$
- c) $\mu = 0.25$
3. Analysis of results

It is clear from Figure 5 that the coefficient of contact friction $\mu$ has a significant impact on the course of rock medium failure. For minute values of this coefficient (Figure 5a, b) in the initial stage of penetration, the crack develops deep into the material (angle $\alpha$ takes negative values in this phase). In the next phase, the crack begins to move towards the free surface of the model. As the value of the friction coefficient increases (Figure 5c, d) the crack penetrates clearly towards the free surface. The angle $\alpha$ values at the initial stage of the crack development are greater than zero. Further increase of the friction coefficient (Figure 5e, f) does not cause such an intensive change in the crack propagation.

Figure 6. Effect of contact friction coefficient on the course and extent of the rock failure trajectory: d) $\mu = 0.75$, e) $\mu = 1.0$, f) $\mu = 1.5$. 

Figure 6.

- **d)** $\mu = 0.75$
- **e)** $\mu = 1.0$
- **f)** $\mu = 1.5$
4. Conclusions
The analysis showed an incredibly significant influence of the friction coefficient in the contact zone of the undercut anchor head with the rock. Under the conditions of field investigations, one may expect, even within the same rock formation, varied loosening, depending on local rock mass conditions, e.g., degree of rock moisture. Moisture may significantly affect the value of the friction coefficient and thus the extent of the failure zone in the rock medium.

References
[1] Różyło P, Wysmulski P and Falkowicz K 2017 Fem and experimental analysis of thin-walled composite elements under compression Int. J. Appl. Mech. Eng. 22
[2] Falkowicz K and Debski H 2020 The post-critical behaviour of compressed plate with non-standard play orientation Compos. Struct.s 252 112701
[3] Litak G, Gajewski J, Syta A and Jonak J 2008 Quantitative estimation of the tool wear effects in a ripping head by recurrence plots J. Theor. Appl. Mech. 46 521–30
[4] Rogala J, Gajewski J and Ferdynus M 2020 The Effect of Geometrical Non-Linearity on the Crashworthiness of Thin-Walled Conical Energy-Absorbers Materials 13 4857
[5] Wysmulski P, Debski H, Falkowicz K and Rozylo P 2019 The influence of load eccentricity on the behavior of thin-walled compressed composite structures Compos. Struct. 213 98–107
[6] Falkowicz K, Debski H and Wysmulski P 2020 Effect of extension-twisting and extension-bending coupling on a compressed plate with a cut-out Compos. Struct. 238 111941
[7] Mahrenholtz P 2013 Experimental performance and recommendations for qualification of post-installed anchors for seismic applications (Stuttgart: IWB)
[8] Hoehler M S, Mahrenholtz P and Eligehausen R 2011 Behavior of Anchors in Concrete at Seismic-Relevant Loading Rates ACI Struct. J. 108
[9] Hoehler M S and Eligehausen R 2008 Behavior and testing of anchors in simulated seismic cracks ACI Struct. J. 105 348
[10] Ashour A F and Alqedra M A 2005 Concrete breakout strength of single anchors in tension using neural networks Adv. Eng. Softw. 36 87–97
[11] Eligehausen R, Mallée R and Silva J F 2006 Anchorage in concrete construction (Berlin: Ernst & Sohn)
[12] Piccinin R, Ballarini R and Cattaneo S 2012 Pullout Capacity of Headed Anchors in Prestressed Concrete J. Eng. Mech. 138 877–87
[13] Watson D S 2006 Modelling aspects of the influence of edge effects on expansion anchors PhD (University of Glasgow)
[14] Lehr B 2003 Tragverhalten von Verbunddübeln unter zentrischer Belastung im ungerissenen Beton - Gruppenbefestigungen und Befestigungen am Bauteilrand
[15] Bocca P, Carpinteri A and Valente S 2018 Fracture Mechanics Evaluation of Anchorage Bearing Capacity in Concrete Applications of Fracture Mechanics to Reinforced Concrete ed A Carpinteri (Boston: CRC Press) pp 231–66
[16] Elfgren L and Ohlsson U 2018 Anchor Bolts Modelled with Fracture Mechanics Applications of Fracture Mechanics to Reinforced Concrete ed A Carpinteri (Boston: CRC Press) pp 1–50
[17] Carpinteri A 2018 Applications of Fracture Mechanics to Reinforced Concrete (Boston: CRC Press)
[18] ACI Committee 349 2006 Code requirements for nuclear safety-related concrete structures: (ACI 349-06) and commentary, an ACI standard (Farmington Hills, Mich.: American Concrete Institute)
[19] Fuchs W, Eligehausen R and Hofmann J 2020 Bemessung der Verankerung von Befestigungen in Beton: EN 1992-4, der neue Eurocode 2, Teil 4 Beton- und Stahlbetonbau 115 36–44
[20] Ahmed L T and Braimah A 2017 Behaviour of undercut anchors subjected to high strain rate loading Procedia Eng. 210 326–33
[21] Benedetti L, Cervera M and Chiumenti M 2016 High-fidelity prediction of crack formation in 2D and 3D pullout tests Comput Struct. 172 93–109
[22] Cusatis G, Di Luzio G and Rota M 2003 Simulation of headed anchor failure Computational Modeling of Concrete Structures (Procs., EURO-C 2003 Conference), St. Johann im Pongau, Austria pp 683–8
[23] Hariyadi, Munemoto S and Sonoda Y 2017 Experimental Analysis of Anchor Bolt in Concrete under the Pull-Out Loading Procedia Eng. 171 926–33
[24] Pallarès L and Hajjar J F 2010 Headed steel stud anchors in composite structures, Part I: Shear J. Constr. Steel Res. 66 198–212
[25] Pallarès L and Hajjar J F 2010 Headed steel stud anchors in composite structures, Part II: Tension and interaction J. Constr. Steel Res. 66 213–28
[26] Mahrenholtz P and Eligehausen R 2015 Post-installed concrete anchors in nuclear power plants: Performance and qualification Nucl. Eng. Des. 287 48–56
[27] Fuchs W, Eligehausen R and Breen J E 1995 Concrete capacity design (CCD) approach for fastening to concrete Struct J. 92 73–94
[28] Di Nunzio G 2019 A Literature Review about the head-size effect on the capacity of cast-in anchors Proceedings of the 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures (IA-FraMCoS)
[29] Siegmund M, Kalita M, Balaga D, Kaczmarczyk K and Jonak J 2020 Testing the rocks loosening process by undercutting anchors Stud. Geotech. Mech. 42 276–90
[30] Jonak J, Karpiński R, Siegmund M, Machrowska A and Prostański D 2021 Experimental Verification of standard recommendations for estimating the load-carrying capacity of undercut anchors in rock material Adv. Sci. Technol. 15(1) 230–44
[31] Jonak J and Siegmund M 2019 FEM 3D analysis of rock cone failure range during pull-out of undercut anchors IOP Conf. Ser.: Mater. Sci. Eng. 710 012046
[32] Jonak J, Siegmund M, Karpiński R and Wójcik A 2020 Three-Dimensional Finite Element Analysis of the Undercut Anchor Group Effect in Rock Cone Failure Materials 13 1332
[33] Jonak J, Karpiński R, Siegmund M, Wójcik A and Jonak K 2020 Analysis of the Rock Failure Cone Size Relative to the Group Effect from a Triangular Anchorage System Materials 13 4657
[34] Jonak J, Karpiński R, Wójcik A and Siegmund M 2021 The Influence of the Physical-Mechanical Parameters of Rock on the Extent of the Initial Failure Zone under the Action of an Undercut Anchor Materials 14 1841
[35] Jonak J, Karpiński R and Wójcik A 2021 Influence of the Undercut Anchor Head Angle on the Propagation of the Failure Zone of the Rock Medium Materials 14 2371
[36] Jonak J, Karpiński R and Wójcik A 2021 Influence of the Undercut Anchor Head Angle on the Propagation of the Failure Zone of the Rock Medium—Part II Materials 14 3880