Numerical analysis of deep twin excavations and boreholes for heavy oil production

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Abstract. One of the plans for the production of Turkey's largest oil reserve, Bati Raman (1.85 billion barrels), is to use Mining-Assisted Heavy Oil Production (MAHOP). In this method, twin declines are excavated from the surface to the reservoir and a series of excavations (galleries) continue along the bottom of the reservoir. Fan-shaped steam injection and production holes are drilled in the reservoir from the crown of the galleries to use conventional Steam-Assisted Gravity Drainage (SAGD). The Bati Raman reservoir is situated at an average depth of 1450 m, producing 12° API heavy oil from a 60m thick calcareous reservoir rock. This research aims to numerically investigate the stability of excavations together with the initiation, formation and propagation of fracture networks between the fan-shaped boreholes and around typical twin excavations using FLAC3D. It is shown that the stability of twin excavations and pillars between them can be guaranteed with suitable support types. In addition, this innovative approach in heavy oil production in hard rock media successfully showed that the fracture networks created by MAHOP could be used effectively for oil recovery of reservoir rocks using SAGD.

1. Introduction
The increase in oil demand and the decrease in natural resources encourage engineers to try out innovative solutions for oil production. One solution is resorting to more efficient methods at more challenging conditions instead of conventional techniques. Heavy oil production at great depths by conventional methods requires such a solution. Crude oil with API gravity of 12° is classified as heavy oil that is heavier than water and sinks in it and requires heavy oil recovery techniques to be adopted to be produced. Numerous conventional heavy oil recovery methods are in use, such as drilling vertical wells, pumping and creating a high-pressure difference on oil. However, recovery rates of conventional methods are highly inefficient; for this reason, different technologies are adopted to develop efficient solutions such as thermal and cold methods by targeting two factors; gravity and the viscosity of heavy oil. These unconventional methods include Vapour Extraction (VAPEX) method, CO₂, water and diluent steam injection techniques which is creating a vapour chamber in the reservoir by injecting vaporised solvents, Steam-Assisted Gravity Drainage (SAGD) method that is making the oil more mobile by injecting hot steam from one of the two parallel wells and collecting less viscous oil from the other. In general, steam usage in heavy oil production gives the most encouraging recovery rates, even if these methods have their unique challenges [1]. Another way for heavy oil production is Mining Assisted Heavy Oil Production (MAHOP). In this method, tunnels or shafts are used to reach the reservoir, and a series of excavations continue along the bottom of the reservoir. Fan-shaped steam injection and production holes are drilled in the reservoir from the galleries' crown to use steam-assisted
gravity drainage [2]. Steam injection is done from the bottom of the reservoir. The area that will be water-wetted is more controlled in creating a more accessible injection domain by considering the exposed reservoir surface and fractured rock mass induced by the excavations.

This study aims to numerically investigate the stability of excavations and the initiation, formation and propagation of fracture networks between the fan-shaped boreholes and around typical twin excavations, which are planned to be used in the Bati Raman oil field MAHOP application using FLAC3D.

2. Recent studies on MAHOP
Theoretical studies and practical applications on MAHOP should be reviewed carefully to understand the possibilities and consider the difficulties that come with the method. Even though the literature directly on the MAHOP method is relatively narrow, a combination of literature on deep tunnelling studies, heavy oil production by SAGD, and modelling rock fracturing processes can provide sufficient information creating the required relation between these branches.

Current research carried on a physical laboratory model of the MAHOP proved that the oil recovery reaches up to 70% with a MAHOP carried on five fan-shaped up holes at 100°C steam injection [2]. It is argued that MAHOP is expected to perform better due to less steam loss and better steam quality. The total average capital cost of MAHOP is estimated to be $2.75 billion US dollar, including surface and subsurface facilities. Total capital costs for 60% and 80% recoveries are 2.75 and 1.97 $/bbl, respectively. MAHOP operating cost is estimated to be 12 $/barrel.

In contrast, in the SAGD with vertical holes from the surface case, the total average capital cost is estimated to be $7.62 billion US dollar, including surface facility and drilling horizontal well pairs. Total capital costs for 60% and 80% recoveries are 7.62 and 5.46 $/bbl, respectively. SAGD operating cost is estimated to be 20 $/barrel. As a result, MAHOP is found to be more economical in terms of both initial investment and operating costs [3].

2.1. Bati Raman oil field and Garzan Formation
Different methods were applied to Turkey's largest oil field, Bati Raman, after the discovery of the field in 1961. The location of the field in southeastern Anatolia covers an area of 52.6 km². The entire reserve is in the Garzan formation, which is fractured limestone. Field's permeability water-oil contact was extending in the east-west direction. The average matrix porosity in Garzan formation is 18% (varying 10-25% rates). Although the matrix permeability varies between 10 and 100 millidarcies, the effective permeability very high measurement indicates secondary porosity from the logging results of Formation Micro Imager (FMI). The crack structure and permeability of the double-porous system and the increase of the cracks towards the West increase the uncertainty in the field characterisation. The field's primary production mechanism is rock and fluid expansion, and a not very active water repellant is known to exist. The area has 12 API ° heavy oil density [4]. The Garzan field has its pay zone located at an average depth of 1450m in the ground with an extent of 17 km. The zone width is between 2.4 km and 4.5 km, and the average zone thickness is 64 m. There is a water-reservoir contact at the bottom of the limestone reservoir strata [4]. There is also another water-oil contact at 600 m [5].

The field started production in 1961. The primary production was estimated to be 1.5% of the oil in place [5] [6]. Noticeable improvement was experienced between 1965-1970 by increasing production wells from 130 barrels/day to 9000 barrels/day. In 1974, the daily production was halved with a decrease in field pressure [5]. After 1986, carbon dioxide injection, one of the secondary production techniques, has been applied and continues to be used. In this way, 6% of the oil was produced in the reservoir [6]. As a result of all these applications with the current carbon dioxide injection, the site is foreseen to reach a maximum of 10% recovery [5].
3. Laboratory work
To investigate the geomechanical properties of the reservoir rock (Garzan limestone), a series of deformability and triaxial compression tests performed on Garzan limestone. Tests conducted according to the ISRM suggested methods for rock characterisation standards. Samples were taken from adjacent wells from an average depth of 1100 m. A set of prepared rock core specimen can be seen in figure 1.

![Figure 1. Garzan limestone rock specimen set.](image)

3.1. Determination of intact rock and rock mass properties
A servo-controlled testing machine, MTS 793, was used for rock testing. Post-peak behaviour of rock samples was investigated during the tests. Axial and lateral displacements were recorded with extensometers during uniaxial compression tests. Average results for heavy oil bearing Garzan limestone are shown in Table 1.

| UCS  \(\sigma_{ci}\) (MPa) | Tensile strength \(T_o\) (MPa) | Young's modulus \(E_i\) (GPa) | Poisson's ratio \(\nu\) | Mass density \(\gamma\) (kg/m\(^3\)) | Bulk modulus \(K\) (GPa) | Cohesion \(C\) (MPa) | Friction angle \(\Phi\) (°) |
|----------------|-----------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|
| 6.4            | 0.5             | 4.7             | 0.24            | 2166            | 14             | 2.6            | 36             |

Figure 2 shows typical triaxial test results for intact rock samples. The tests were carried out at 10 and 15 MPa confining stresses. It should be noted that the tests have been carried out with a limited number of samples available, therefore, the variability of the measured parameters could not be determined. More tests are required for the future studies.
4. Numerical analysis
In this study, the stability analysis of excavations and rock mass behaviour around the steam injection well openings were investigated with finite-difference code FLAC3D (Itasca, 2017) [7]. Flac suits this problem because it can handle complex behaviours, which might be a problem for finite element codes, such as problems with multiple stages and large displacements and strains. Mohr-Coulomb failure criterion is used because of the homogeneous behaviour of the limestone.

4.1. Model geometry and boundary conditions
The model geometry contains two parallel circular 4 m diameter TBM tunnels 20 m apart from each other with a length of 18 m. Each TBM segment is assumed as 6 m long. The tunnels are located 20 m above the bottom of the model. The model has a height of 68 m, a length of 18 and a width of 68 m. The domain is selected to represent a homogenous zone with regard of the tested rock specimens. Above these tunnels, there are 30 borehole excavation zones grouped above the TBM tunnels shields 5 in each. The boreholes are placed on the same plane with 30° apart, starting +30° above from the horizontal x-axis. Mentioned dimensions can be seen in figure 3. The diameter of all borehole excavations is 0.2 m. Lengths are 11 m, 14 m, and 20 m. TBM tunnel support is represented by 0.2m thick circular zones around the tunnel.

Normal and horizontal stress of 31.4 MPa is applied to the model to simulate initial stress conditions before excavations. Vertical stress is calculated based on the overburden depth of 1100 m which is selected according to the depth of tested sample locations. The ratio of major and minor horizontal principal stresses to vertical stress is assumed to be in the hydrostatic stress state. These in-situ stresses are initialised in the model prior to excavations. In order to represent deep tunnelling conditions, roller boundaries are applied on the sides, and the top of the model and gridpoints on the bottom side are fixed on each axis. After guaranteeing the initial stress conditions without material failure, by giving high material properties in the first stage, excavations are simulated by removing the material stage by stage with the proper material properties. TBM concrete supports are assumed to be elastic with 0.2 m thickness, 25 GPa elastic modulus, 0.15' Poisson's ratio. Grout injection, liner supports, cutterhead and shield properties of the TBM are not considered in this study. The origin is placed in the middle of the pillar between two tunnels.
Figure 3. Geometry, dimensions and boundary conditions of the model used in the analysis.

5. Results and discussion
The model converged to 1 after 6609 steps. Figure 4 shows the unbalanced force magnitude and the stress states of each axes over the model-step time at the centre of the pillar.

Figure 4. Unbalanced force magnitude (left), and the stress state at the origin (right) after 6609 steps.

Displacements of 1 to 3 cm between the boreholes in the model are observed during the excavation stage of the holes. The study revealed that the boreholes did not affect the top strata. Figure 5 shows the
profiles located for data collection interpretation. The origin location at (0,0,0) is represented with an asterisk in figure 5. Profiles lie parallel to the XY plane and moves on the Y=0 plane which cuts the tunnels in the middle. The profile lines are placed starting at the tunnel centerline and continue for 10m interval for each line.

![Figure 5. The origin history location and profile locations.](image)

![Figure 6. Z displacement profiles.](image)
In figure 6, it can be seen that the drillhole excavations affected the profiles significantly. At the top right graph numbered in figure 6, there is a fluctuation along the profile 3. In figure 7, the two plots show the zone displacement magnitude along the midplanes of the model. In order to observe the fracture network formed by the boreholes only, gridpoint displacement is initialised. The displaced zones, which represents the failed zones, are accumulated between the boreholes. For the calculation steps, the displacements occur right after the instantaneous borehole drills, and the fracture or yield propagation does not increase while getting closer to the equilibrium that shows the ultimate failure is not possible.

![Zone displacement magnitude contours on the model midplanes.](image)

**Figure 7.** Zone displacement magnitude contours on the model midplanes.

6. Conclusion
A numerical analysis is performed to analyse zonal displacements above the tunnels and around the borehole excavations to simulate the rock mass conditions prior to the MAHOP method application. The numerical analysis showed that the fracture networks can be initiated with borehole excavations around the tunnels. In this case still the dominant factor on the ground disturbance was the tunnel excavations. However, when the purpose of these boreholes reconsidered, it should be understood that the steam injection holes will modify the ground conditions once again after the excavations. The resultant plasticity state of borehole excavations may be kept undisturbed but ready for the steam injection to avoid any ultimate failure. Therefore, one way to create more fractures around boreholes may be increasing the number of holes, or the diameter of holes. In this way sweeping of a larger area above the tunnels may be achieved. Thus, the proposed geometry can improve the MAHOP method application. It can be concluded that the drilling pattern of the boreholes should be considered to increase the interaction between the fracture networks around the boreholes. Boreholes can be drilled in a zigzag pattern which can create more fracture intrusion between the holes. It is also concluded that the borehole fracture propagation does not move along the borehole axis which means to reach the upper reservoir strata longer boreholes may be used. Another simulation can be conducted with the case where boreholes of the parallel tunnel excavations meet over the pillar between the tunnels. Different drilling patterns, and more exclusively the rock-fluid interaction must be investigated to understand the MAHOP method thoroughly.
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