

# Effects of Cavity Size and Number on the Mechanical Behavior of Marl under Uniaxial Compression

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**Abstract:** Underground cavities significantly alter the load-bearing paths and failure behavior of rock masses. This study experimentally investigates the effects of cavity size and number on the mechanical behavior and fracture evolution of marl under uniaxial compression. Twenty-four rectangular specimens measuring  $50 \times 50 \times 100$  mm were prepared, including intact specimens, specimens containing a single circular cavity with diameters of 3, 6, 9, and 12 mm, and specimens containing two to four aligned cavities with a constant diameter of 3 mm. Three replicate specimens were tested under each of the eight conditions. Acoustic emission (AE) and two-dimensional digital image correlation (DIC) were synchronously employed to monitor internal cracking and surface deformation. As the cavity diameter increased from 3 to 12 mm, the mean peak stress decreased from 50.90 to 32.39 MPa. Compared with intact specimens, the maximum reductions in peak stress and elastic modulus were 39.7% and 46.65%, respectively. Increasing the cavity number from one to four reduced the mean peak stress from 50.90 to 32.95 MPa. Cavity-containing specimens also exhibited multiple post-peak stress drops, local stress recovery, and staged residual load-bearing, indicating progressive failure through localized cracking and stress redistribution.

**Keywords:** Underground cavities, Uniaxial compression.

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## 1. Introduction

Underground cavities are commonly encountered in transportation, mining, and urban underground engineering. They may be formed naturally by long-term dissolution in karst regions or artificially by underground excavation, mining activities, and construction-induced disturbance. The presence of a cavity disrupts the continuity of the rock mass and changes its original load-transfer path. Under external loading, stress concentration develops around the cavity boundary, promoting localized damage, crack initiation, and crack propagation. Progressive crack coalescence may eventually cause overall instability or surface collapse, posing a serious threat to the safety of overlying engineering structures.

The mechanical response of cavity-containing rock is strongly affected by cavity geometry. An increase in cavity size reduces the effective load-bearing area, whereas multiple cavities generate interacting stress fields and weaken the rock bridges between adjacent cavities. Previous experimental and numerical studies have examined the strength, deformation, and failure behavior of rocks containing prefabricated cavities. However, systematic investigations of marl specimens considering both cavity size and cavity number remain limited. In particular, the relationship between macroscopic mechanical degradation, internal acoustic emission activity, and surface strain localization requires further investigation.

In this study, uniaxial compression tests were conducted on 24 marl specimens with different cavity configurations. The specimens included intact samples, single-cavity samples with diameters of 3, 6, 9, and 12 mm, and multiple-cavity samples containing two, three, or four aligned cavities with a constant diameter of 3 mm. Three replicate specimens were tested for each condition. Acoustic emission and two-dimensional digital image correlation were synchronously employed to monitor internal cracking and surface deformation. The effects of cavity size and number on the stress-strain response, peak stress, elastic modulus, post-peak

behavior, and progressive fracture process were investigated. The results provide experimental evidence for evaluating the stability and failure risk of cavity-containing marl in underground and transportation engineering. Previous studies have demonstrated that cavity geometry significantly affects rock strength, stress concentration, and crack propagation under uniaxial compression [1–3].

## 2. Experimental Methodology

### 2.1. Specimen Preparation and Cavity Configuration

Marl blocks were processed into rectangular specimens measuring  $50 \times 50 \times 100$  mm. The end and lateral surfaces of each specimen were carefully ground to ensure dimensional accuracy, surface flatness, and uniform contact with the loading platens. After dimensional processing, circular cavities were created by mechanical drilling according to the experimental design. A total of 24 specimens were prepared and divided into eight groups, with three replicate specimens in each group.

The intact specimens, denoted as J0, were used as the reference group. The single-cavity specimens were designated as J3, J6, J9, and J12 according to cavity diameters of 3, 6, 9, and 12 mm, respectively. These diameters corresponded to 6–24% of the specimen width and provided a gradual variation in cavity size. The multiple-cavity specimens were designated as J32, J33, and J34, representing specimens containing two, three, and four circular cavities, respectively. For these groups, the cavity diameter was fixed at 3 mm to isolate the influence of cavity number.

**Table 1.** Cavity configurations of the marl specimens.

| Group | Number of cavities | Diameter (mm) |
|-------|--------------------|---------------|
| J0    | 0                  | —             |
| J3    | 1                  | 3             |
| J6    | 1                  | 6             |
| J9    | 1                  | 9             |
| J12   | 1                  | 12            |
| J32   | 2                  | 3             |
| J33   | 3                  | 3             |
| J34   | 4                  | 3             |

All cavities were arranged along the central line of the specimens. For the multiple-cavity groups, the spacing between adjacent cavities was maintained at greater than  $1.5d$ , where  $d$  denotes the cavity diameter. This arrangement retained a rock bridge between neighboring cavities while allowing the interaction between the corresponding stress-concentration regions to be investigated. The specimen configurations were designed to separately evaluate the effects of cavity size and cavity number on the strength, deformation, stiffness degradation, and fracture behavior of marl under uniaxial static compression.

## 2.2. Uniaxial Compression Test

Uniaxial compression tests were conducted using an RMT-301 rock and concrete mechanics testing system. Before each test, the specimen surfaces were cleaned, and the specimen was positioned between the upper and lower loading platens. The central axis of the specimen was carefully aligned with the loading direction to minimize eccentric loading and ensure that the axial force was uniformly applied to the specimen ends.

The tests were performed under displacement control at a constant loading rate of 0.001 mm/s. The mechanical loading system, acoustic emission system, and digital image correlation system were started simultaneously to obtain synchronized mechanical and fracture-evolution data. During loading, the axial load, axial deformation, lateral deformation, acoustic emission signals, and surface images were continuously recorded.

Loading was continued beyond the peak stress into the post-peak stage. The test was terminated when the applied load approached a relatively stable residual level and the principal macroscopic failure characteristics of the specimen had developed. The recorded load and deformation data were used to obtain the complete stress–strain curves and determine the peak stress, peak strain, elastic modulus, and post-peak response of each specimen. Comparisons among the different specimen groups were then performed to evaluate the effects of cavity size and cavity number on the uniaxial compressive behavior of marl.

## 2.3. AE and DIC Monitoring

Acoustic emission (AE) monitoring was employed to record the internal microcracking activity of the marl specimens throughout the loading process. Four AE sensors were attached to different positions on the lateral surfaces of each specimen. Petroleum jelly was applied between each sensor and the specimen surface as a coupling agent to improve elastic-wave transmission. The sensors were connected to preamplifiers and then to the AE acquisition system for signal amplification, transmission, and storage.

The AE system was synchronized with the mechanical

loading system and continuously recorded the signals generated from the initial loading stage to final failure. The acquired AE parameters were subsequently used to characterize crack initiation, propagation, and instability.

Two-dimensional digital image correlation (DIC) was used to measure the full-field surface deformation of the specimens. Before testing, one  $50 \times 100$  mm surface of each specimen was coated with white paint, and a random black speckle pattern was subsequently applied to provide sufficient grayscale contrast for image correlation. During loading, surface images were continuously captured and processed using VIC-2D software. The vertical displacement field and maximum principal strain field were obtained at different loading stages.

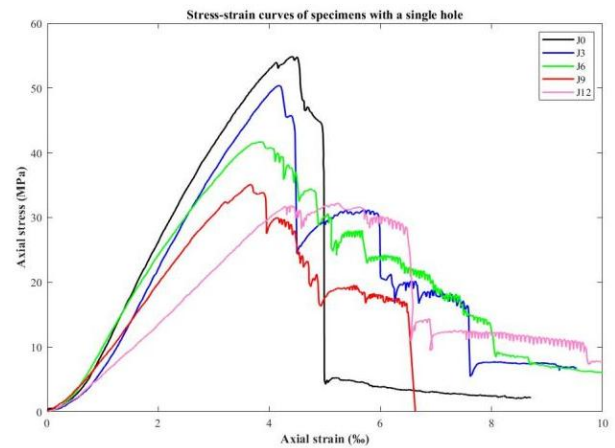
The synchronized mechanical, AE, and DIC measurements enabled the relationships among the stress–strain response, internal cracking activity, surface strain localization, and macroscopic failure process to be examined. The AE data were used to identify changes in microcracking activity, while the DIC results were used to locate strain-concentration regions and track the development of surface cracks around the cavities and rock bridges.

# 3. Results and Discussion

## 3.1. Effect of Cavity Size

The stress–strain curves of all specimen groups exhibited four typical stages: initial compaction, approximately linear elastic deformation, nonlinear crack development, and post-peak failure. Although some differences were observed among the three replicate specimens because of the natural heterogeneity of marl, the test results showed a clear reduction in load-bearing capacity with increasing cavity diameter.

Representative stress–strain curves for specimens with different cavity diameters are presented in Fig. 1.

**Figure 1.** Representative stress–strain curves of marl specimens with different cavity diameters

approximately 5.2%, 21.8%, 34.6%, and 39.7%, respectively. The reduction was particularly pronounced when the cavity diameter increased from 3 to 9 mm. A further decrease was observed from 9 to 12 mm, although the corresponding reduction rate became lower. These results indicate that an enlarged cavity reduces the effective load-bearing area and increases the extent of stress concentration around the cavity boundary.

**Table 2.** Mean mechanical parameters for different cavity diameters.

| Group | Diameter (mm) | Peak stress (MPa) | E (GPa) | D <sub>e</sub> (%) |
|-------|---------------|-------------------|---------|--------------------|
| J0    | —             | 53.70             | 15.859  | 0                  |
| J3    | 3             | 50.90             | 14.498  | 8.58               |
| J6    | 6             | 42.02             | 12.490  | 21.24              |
| J9    | 9             | 35.12             | 11.255  | 29.03              |
| J12   | 12            | 32.39             | 8.461   | 46.65              |

The elastic modulus showed a similar decreasing trend. Its mean value decreased from 15.859 GPa for the intact specimens to 8.461 GPa for the specimens containing a 12 mm cavity, corresponding to a maximum degradation of 46.65%. This indicates that increasing cavity size weakened both the peak load-bearing capacity and the pre-peak stiffness of the marl specimens.

Cavity size also affected the post-peak response. The intact specimens generally exhibited a relatively concentrated stress drop after reaching the peak stress, whereas the cavity-containing specimens showed multiple stress drops, local stress recovery, and temporary residual load-bearing stages. These features became more evident in specimens with larger cavities. The post-peak fluctuations suggest that failure did not occur instantaneously but developed progressively through localized cracking, stress redistribution, and subsequent crack propagation around the cavity.

### 3.2. Effect of Cavity Number

The effect of cavity number was investigated by comparing the J3, J32, J33, and J34 groups, which contained one, two, three, and four cavities, respectively. The cavity diameter was maintained at 3 mm for all groups so that the influence of cavity number could be examined independently. The representative stress–strain curves are shown in Fig. 2.

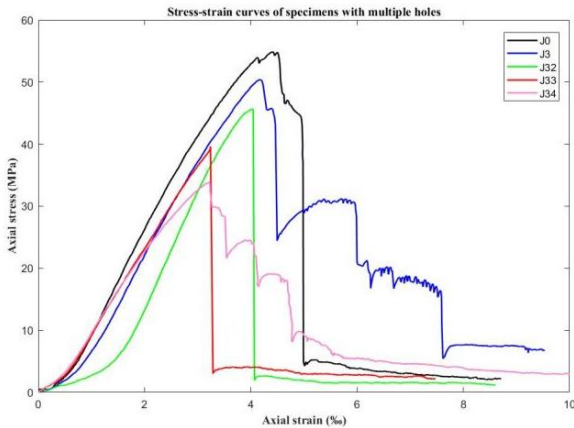


**Figure 2.** Representative stress–strain curves of marl specimens with different numbers of cavities

The mean peak stresses of the J3, J32, J33, and J34 groups were 50.90, 45.66, 40.24, and 32.95 MPa, respectively. Compared with the single-cavity J3 group, the mean peak stresses of the J32, J33, and J34 groups decreased by approximately 10.3%, 20.9%, and 35.3%, respectively. The reduction between successive groups was not uniform. Increasing the cavity number from one to two and from two to three produced reductions of 10.3% and 11.9%, respectively, whereas an 18.1% reduction occurred when the cavity number increased from three to four. This result indicates that the weakening effect became more pronounced in the four-cavity specimens.

**Table 3.** Mean mechanical parameters for different numbers of cavities.

| Group | Number | Mean peak stress (MPa) | Mean E (GPa) | D <sub>e</sub> (%) |
|-------|--------|------------------------|--------------|--------------------|
| J0    | 0      | 53.70                  | 15.859       | 0                  |
| J3    | 1      | 50.90                  | 14.498       | 8.58               |
| J32   | 2      | 45.66                  | 12.709       | 19.86              |
| J33   | 3      | 40.24                  | 12.407       | 21.77              |
| J34   | 4      | 32.95                  | 11.028       | 30.46              |

The mean elastic modulus also decreased with increasing cavity number. Relative to the intact J0 group, the elastic modulus degradation increased from 8.58% for the single-cavity specimens to 30.46% for the four-cavity specimens. However, the difference between the J32 and J33 groups was relatively small, indicating that stiffness degradation did not increase uniformly with cavity number.

The reduction in peak stress and elastic modulus can be attributed to the decrease in the effective load-bearing area and the interaction of the stress-concentration regions around neighboring cavities. As the number of cavities increased, the rock bridges between adjacent cavities became more susceptible to localized damage and crack propagation. The four-cavity specimens also exhibited pronounced multiple stress drops, local stress recovery, and temporary residual load-bearing after the peak stress, indicating a progressive failure process involving repeated local fracture and stress redistribution. Similar reductions in strength and stiffness with increasing cavity number have also been reported for sandstone and jointed rock-like specimens [4, 5].

### 3.3. AE and DIC Characteristics

The AE activity exhibited a clear stage-dependent evolution during uniaxial static compression. During the initial compaction stage, only limited AE ring counts and energy releases were recorded. The AE events remained relatively sparse in the approximately linear elastic stage. As the applied stress approached the peak value, both the AE event rate and energy release increased markedly, indicating the rapid initiation and propagation of microcracks. Pronounced AE bursts generally coincided with sudden stress drops, reflecting the occurrence of local fracture and stress redistribution. After the principal failure event, the cumulative AE parameters tended to increase more slowly as the specimens entered the residual load-bearing stage...indicating the rapid initiation and propagation of microcracks [6, 7].

The DIC results further revealed the spatial evolution of surface deformation. The vertical displacement field and maximum principal strain field showed that strain localization initially developed near the cavity boundaries, particularly on both sides of the cavities. With increasing load, the localized zones gradually extended along inclined paths and subsequently developed into macroscopic fracture bands. For the single-cavity specimens, strain concentration was mainly distributed around the two sides of the cavity and propagated toward the specimen boundaries. In the multi-cavity specimens, interaction between the stress-concentration zones of adjacent cavities produced a more complex strain distribution. Pronounced localization occurred within the rock bridges between cavities, promoting crack interaction and eventual coalescence...subsequently developed into macroscopic fracture bands [1, 7].

The correspondence among stress drops, AE bursts, and

DIC strain-localization bands demonstrates that the failure of cavity-containing marl was a progressive process involving crack initiation, stable propagation, localization, and final coalescence. The combined AE and DIC observations also indicate that cavity configuration controls not only the load-bearing capacity but also the crack-propagation path and macroscopic failure pattern.

## 4. Conclusions

Uniaxial static compression tests combined with AE and DIC monitoring were conducted to investigate the effects of cavity size and number on the mechanical behavior and progressive failure of marl. The main conclusions are as follows.

(1) Increasing the cavity diameter significantly reduced the load-bearing capacity and stiffness of the marl specimens. As the cavity diameter increased from 3 to 12 mm, the mean peak stress decreased from 50.90 to 32.39 MPa. Compared with the intact specimens, the maximum reductions in peak stress and elastic modulus were 39.7% and 46.65%, respectively.

(2) Increasing the cavity number also weakened the mechanical properties of marl. When the number of 3-mm-diameter cavities increased from one to four, the mean peak stress decreased from 50.90 to 32.95 MPa, while the mean elastic modulus decreased from 14.498 to 11.028 GPa. The interaction between adjacent stress-concentration zones weakened the rock bridges and promoted crack interaction and coalescence.

(3) AE activity was weak during the initial compaction and approximately linear elastic stages but increased markedly near the peak stress. DIC results showed that deformation localization initially developed around the cavity boundaries and subsequently propagated toward the specimen boundaries or adjacent cavities. The agreement among stress drops, AE bursts, and DIC localization patterns confirms that failure occurred progressively through crack initiation, propagation, interaction, and final coalescence.

These results demonstrate that both cavity size and number

govern the mechanical degradation and failure evolution of marl, providing an experimental basis for assessing the stability of cavity-containing rock masses.

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