A discontinuum analysis of underground cavern

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Abstract: Underground gas storage is a relatively recent technique, which has been developing rapidly in the last years as it is safer, more environmentally friendly, publicly accepted and technically and commercially attractive under favourable geological conditions. In the past, when natural gases were stored underground, they were deposited in caverns without wall protection or ground water control. Nowadays however, more efficient storage systems are available, where water curtains and refrigeration systems are applied.

One of the most common problems encountered while constructing underground cavities for storing highly pressurised Liquified Natural Gas (LNG) is the stability of the rock structure. The strength of the rock formation is governed by the strength of its discontinuities, joints and bedding planes which, in turn, dictate the strength and the state of stress around the cavern itself. As a result, the structural stability of the cavity needs to be carefully analysed, using numerical modelling tools based on both continuum and discontinuum models. This paper focuses on the stress deformation response of twin tunnels of varying diameters, at different spacing between the two tunnels and subjected to different internal pressures through a discontinuum analysis carried out using UDEC.

One of the main conclusions drawn from this analysis was that the minimum critical distance to be maintained between twin circular tunnels was four times the distance of their diameter. It is also important to note that an increase in the internal gas pressure of the tunnel appeared to cause an increase in the X-displacement and a decrease in the Y- displacement at the crown and springing levels.

Résumé: Par rapport au stockage en surface, le stockage souterrain a des avantages vis-à-vis de la sécurité et de l'environnement, et peut être commercialement intéressant lorsque les conditions géologiques sont favorables. Il est aujourd'hui préférable de stocker le gaz naturel liquéfié (GNL) et le gaz de pétrole liquéfié (GPL) dans des cavernes souterraines pour raisons de sécurité et d'acceptation par le public. Dans le passé, les gaz naturels étaient stockés dans des cavernes sans protection de paroi ou contrôle des eaux souterraines, mais des systèmes de stockage modernes plus efficaces utilisant rideaux d'eau et réfrigération sont désormais disponibles pour le stockage du gaz. Lorsque le GPL est stocké sous haute pression dans les cavernes souterraines, la stabilité de la structure doit être soigneusement examinée. Une analyse minutieuse des formations rocheuses complexes et souvent fracturées qui sont habituellement rencontrées lors de la construction des cavernes souterraines est nécessaire. La stabilité d'une caverne rocheuse dépend plus ou moins de l'état de contrainte autour de la caverne et de la robustesse de la formation rocheuse. Cette dernière est régie par la solidité de ses discontinuités, joints ou plans de stratification, et ne doit jamais être négligée lors de la conception et l'analyse d'une caverne rocheuse.

La stabilité structurale de la cavité souterraine doit être analysée au niveau microscopique par des outils de modélisation numérique basés sur des modèles de milieu continu et discontinu. Ce papier se concentre sur les analyses numériques utilisant des modèles de milieu discontinu bases sur un modèle de tunnel bitube. L'effet de la pression interne sur la réponse en contrainte-déformation de la formation rocheuse autour du tunnel ainsi que l'effet de la distance entre les tubes et leur diamètre ont été considérés afin d'évaluer l'interaction entre les tubes. La modélisation en milieu discontinu pour la présente étude a été effectuée avec le code UDEC (Universal Distinct Element Code).

Keywords: rock mechanics, numerical models, cavern, stability, stress, deformation

INTRODUCTION

Gas in nature is safely residing for millions of years under good competent rock. The technique however, of storing gases in man made caverns has a relatively short history. Underground storage of natural gas was first practised in 1915 in North America in converted oil and gas fields. At a later stage, storage space was created by injecting gas into water filled rock formations (aquifers) underlying good quality rock. Staring with a few Liquefied Natural Gas (LNG) installations in caverns without wall protection or ground water control, gradually more efficient storage systems were developed using water curtains and refrigeration. Today's development has enabled the underground storage of Liquefied Petroleum and Natural Gases. The main reason for this being the public acceptance and the fact that underground storage is by far safer than the previous gas storage methods applied. The high vapour pressure of the LPG requires caverns of high stability that are located at great depths below the ground level. The rock formations that are encountered at great depths are usually complicated and well fractured and therefore require careful analysis prior to the design and construction of the cavern.

The stability of a rock cavern is more or less dependent upon the strength of the rock formation and the state of rock stress around the cavern i.e. the ratio of horizontal to vertical rock stress. The strength of the rock formation is governed by the strength of its discontinuities, joints or bedding planes and should never be overlooked while analysing a rock cavern. The paper focuses on the stress-deformation response of a twin tunnel constructed with different diameters at different spacing subjected to different internal pressures through a discontinuum analysis carried out using UDEC.

NEED FOR UNDERGROUND STORAGES

Underground rock cavern petroleum storage facilities are common in many countries worldwide. A variety of petroleum products can be stored in rock caverns, including crude oil, petrol and LPG. Operations of the underground petroleum storage facilities are very similar to storage facilities above ground. The oil is stored underground and the surface land is freed from oil tank farms. The most economical surface storage of LPG requires very large refrigerated tanks. These tanks and their associated plant are costly to build and maintain. The refrigerated tanks also have a finite life of possibly less than 30 years. Underground storage on the other hand is less expensive to build and requires little or no maintenance. The plant associated with the underground storage caverns is relatively simple, easy to maintain and can be easily replaced when worn out. Another big advantage of underground storage is that it does not intrude at all on the surface environment.

LPG STORAGE

Liquefied Petroleum Gas (LPG) has successfully been stored underground in unlined rock caverns for the last three decades. LPG is either stored at nearly atmospheric pressure at low temperatures (refrigerated storage) or pressurised at ambient rock temperature (pressurised storage). The containment of both is controlled by the ground water in the rock fracture network surrounding the cavern. In order to secure containment the storage must be located at a sufficient depth below the ground water surface. Liquefied petroleum gases are a mixture of propane and butane with various compositions and properties. Pure propane may be stored as LPG at –42°C at atmospheric pressure in a fully refrigerated storage. Any temperature increase will induce boiling, which will continue until the pressure reaches a value that matches the vapour pressure curve for propane. In the refrigerated storage, the containment of LPG is secured by the water saturated frozen zone surrounding the caverns and the free water that must be allowed above the 0°-isotherm. If LPG is to be stored in a fully compressed storage, the required pressure, i.e the required depth below the ground water table is determined by the storage conditions of the product and the ambient rock temperature. Containment must be ensured at all times for safety, environmental and economical reasons. The gas must therefore be stored at pressures below its “critical pressure” taking into account the influence on geometric factors such as shape, dimensions and the number of parallel caverns present etc. In general the required depth for pressurized storage is greater than that of refrigerated storage.

CNG AND LNG STORAGE

The storage conditions for natural gas are more extreme than those for petroleum gases. The gas is either stored at extremely high pressures in the gas phase as compressed natural gas (CNG) or in liquid state as LNG. CNG can be stored in either Lined Rock Caverns (LRC) or in deep, large and water-sealed unlined caverns (hydraulically compensated). The containment principles for the unlined alternative are comparable to the compressed LPG storages. However, in order to increase the storage density and storage volume the gas may be stored in the cavern excavated at a depth below the ground water table. Alternatively the gas may be stored in LRCs at more moderate depths. The LRCs may be constructed for pressures up to 200 bar, increasing the density about 200 times, with a rock cover of only 100 to 200 metres. The wall structure of thick steel, concrete and drainage system and its interaction with the bedrock is designed to contain the gas and bear the pressure. Maximum storage pressure is stipulated by the rock mass condition, the deformability and its interaction with the lining system.

ADVANTAGES OF UNDERGROUND STORAGES

The utilisation of underground space has many advantages in comparison to over-ground development, some of which are listed below:

- Costs for firefighting equipment are relatively low.
- Land costs are relatively low because of the reduction or elimination of buffer zones.
- Visual impact is low, since there are no bulky storage vessels on the surface.
- Reduced exposure to damage.
- Reduced explosion risk.
- Reduced land requirement.
- Economic benefits.
- Better use of land space.
- Strategic storage of essential products.
- Better environmental quality.
- Reduced reliance on foreign import.

- Improved energy efficiency.
- Better use of material resources.
- Better safety and protection.
- The construction cost for storing about 2,000,000 m^3 in the underground rock cavern is cheaper than the equivalent surface tank storage.
- The maintenance and operation cost for storing more than 50,000 m^3 is low. The cost decreases with increase in storage volume.
- The risk of oil leakage and pollution of the ground water is less than the risk of equivalent over-ground storage facilities.
- Underground storages can be located in earthquake zones.

STORAGE CONCEPTS

The principle of storing liquid petroleum products in rock caverns is illustrated in Figure 1. Petroleum storage caverns are usually unlined and the rock masses surrounding the caverns are reinforced with steel bolts. The cavern is usually constructed at a required depth below the groundwater table. Groundwater is allowed to permeate through the surrounding rock masses into the storage cavern. As stored petroleum products are lighter than water, water is collected at the bottom of the cavern and pumped out from the cavern. In fact, it is important to ensure that surrounding rock masses are saturated with groundwater and the water pressure is higher than the liquid pressure inside the cavern, to ensure that the flow is towards the cavern. This prevents the petroleum products from leaking out of the storage cavern. Alternatively, lined caverns can also be used for underground petroleum storage in rock caverns. For lined caverns, the lining used is impermeable. The stored petroleum products are separated from the surrounding rock masses and the groundwater.

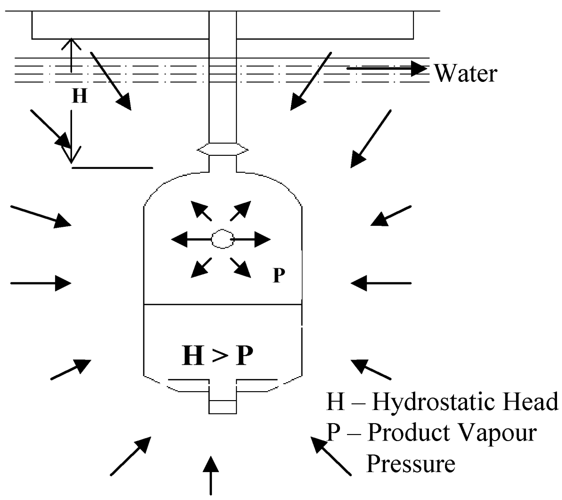

Figure 1. Principle of underground oil storage in unlined rock cavern

Design and construction of rock caverns is based on engineering principles of rock mechanics. Caverns are designed to be unsupported and the surrounding rock masses are used as self-supporting structural materials. However, because the rock masses are discontinuous (fractured), rock reinforcement, usually rock bolts, are used to tie the discontinuous rock masses together, forming a continuous medium.

Construction of cavern involves rock excavation and rock reinforcement. Rock is usually excavated in several stages and the surrounding rock masses are usually reinforced to ensure the long-term stability of the cavern. The commonly available reinforcements are steel bolts, steel cables and shotcrete/fiber reinforced concrete. The development costs of an underground petroleum cavern storage facility of a given capacity depends primarily on the quality of rock masses in which the cavern is to be constructed.

Usually, better quality of rock mass requires less rock reinforcement and hence results in a lower construction cost. The construction costs for an underground storage cavern complex and for an above ground tank farm are of the same order. However, the land saving from using underground storage is economically and socially significant. The cost of constructing rock caverns in sedimentary rocks is usually higher than that in granite (igneous) rock, due to the generally poorer quality of sedimentary rocks.

UNLINED STORAGE

The product can be stored either as a refrigerated storage or as a pressurized storage. The first involves storage at boiling point and at atmospheric pressure. The rock cavern can, in this case, be located at shallow depths. The second method, of pressurized storage, involves storage at a temperature above 0° C and at a gas pressure less than the ground water pressure prevailing around the rock cavern. Owing to these conditions, rock caverns will be situated at relatively great depths below the ground water table.

LINED STORAGE

In the lined storage system, the stability of the storage cavern is obtained from the mechanical strength of the surrounding rock whilst the lining provides the impermeability or “gas tightness” necessary. Because of the way this system operates, the caverns can be situated at relatively shallow depths below the rock surface.

CAVERN GEOMETRY

The analyses considered twin circular tunnels of 7.5 m, 10 m and 12.5 m diameters placed at a depth of 150 m spaced at different clear distances varying from 1D to 4D (D – Diameter of the tunnel). The rock formation is considered to be intact with a single vertical joint passing through the centre of the tunnels. The cavern geometry is shown in Figure 2.

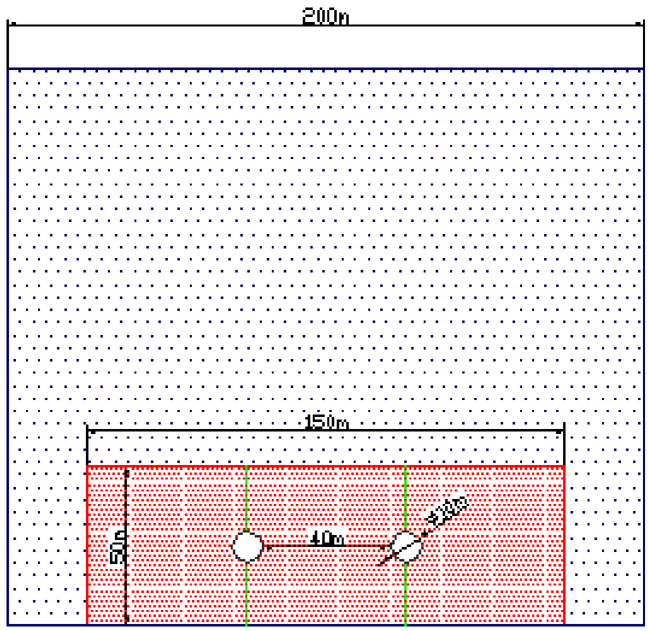

Figure 2. Cavern Geometry

MATERIAL PROPERTIES

Intact Rock Properties:

Unit weight=27.23 kN/m^3
Bulk modulus=20000 MPa
Shear modulus=21818 MPa
Friction angle=35°
Cohesion=2.3 MPa

Joint Properties:

Joint normal stiffness=12000 MPa/m
Joint shear stiffness=1200 MPa/m
Friction angle=22°
Cohesion=0.5 MPa

SOFTWARE USED

The analysis has been carried out using the Universal Distinct Element Code (UDEC) software, which is a two-dimensional numerical program based on the discrete element method for discontinuum modelling. It simulates the response of discontinuous media subjected to either static or dynamic loading. The software is primarily intended for analysis in rock engineering problems, ranging from studies on the progressive failure of rock slopes to evaluations of the influence of rock joints, faults, bedding planes, etc. on underground excavations and rock foundations.

ANALYSIS

The parametric study on the twin circular tunnels considered three variables:

- Diameter of the tunnel (taken as 7.5 m, 10 m and 12.5 m)
- Clear distance between the tunnels (taken as 1 times, 2 times, 3 times or 4 times the tunnel diameter)
- Internal pressures in the tunnel (empty, 1.5 MPa, 3.0 MPa and 4.5 MPa).

The effect of the clear distance between the tunnels and the effect of the internal pressure of the tunnel, on the stress distribution-around the tunnel, at the crown and at the springing levels are analysed. The deformations at the crown and springing levels are also studied.

In order to have an in-depth study of the above parameters, from the problem geometry shown in Figure 2, a block of 150 m × 50 m around the twin circular tunnels has been chosen for a finer zoning of the tunnel region. An overburden of 125 m of rock mass has been simulated by applying a uniform vertical stress of 3.56 MPa on the upper boundary of the problem geometry. The value of 3.56 MPa has been obtained by analysing the complete problem geometry shown in Figure 2 under self weight. The geometry considered is shown in Figure 3.

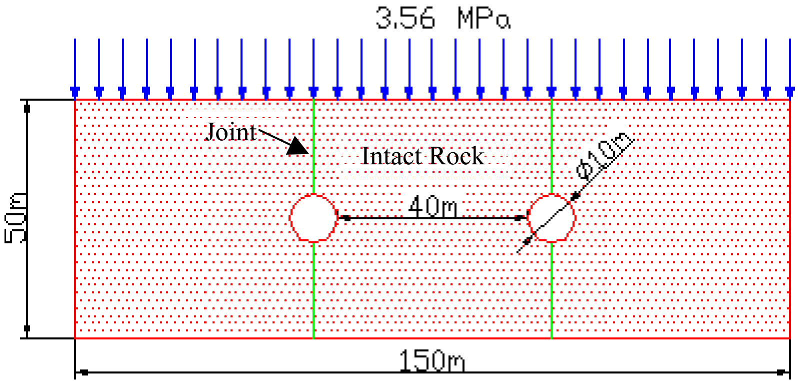

Figure 3. Problem Geometry

RESULTS AND DISCUSSIONS

The stress- deformation response of the twin tunnel system with varying diameters and under different pressure conditions has been the main focus of the present study. The major principal stress contours (σ_1) of the empty tunnel of varying diameter are presented in Figures 4 to 6.

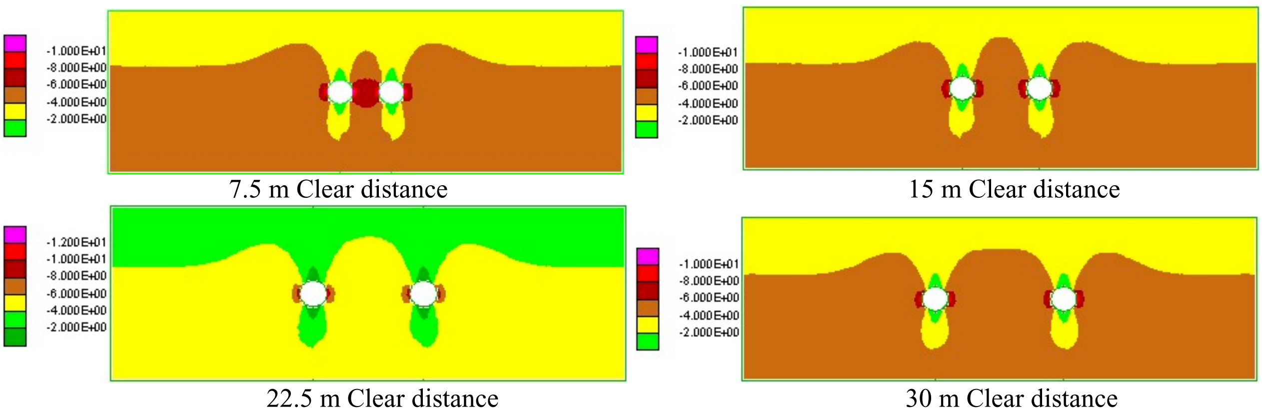

Figure 4. Major Principal Stress Contours for 7.5 m diameter tunnels (Empty)

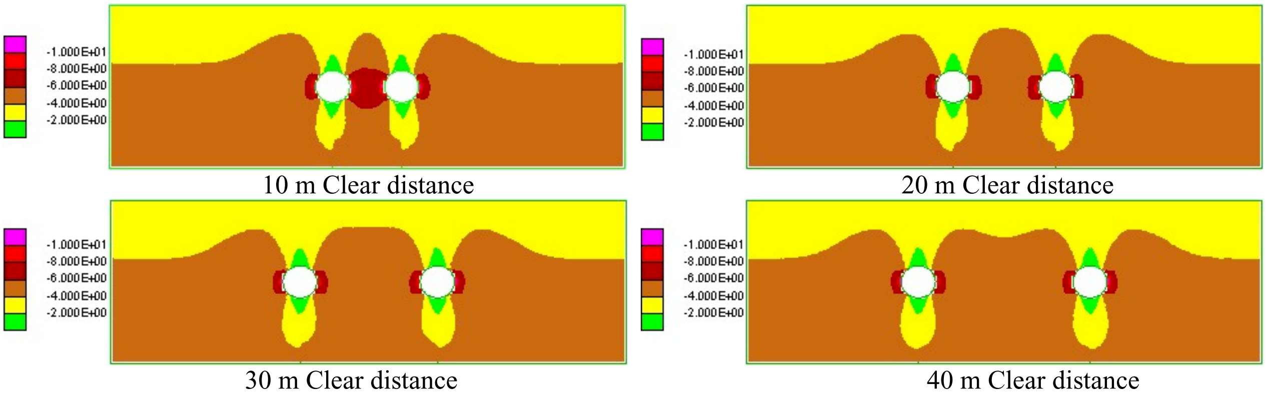

Figure 5. Major Principal Stress Contours for 10 m diameter tunnels (Empty)

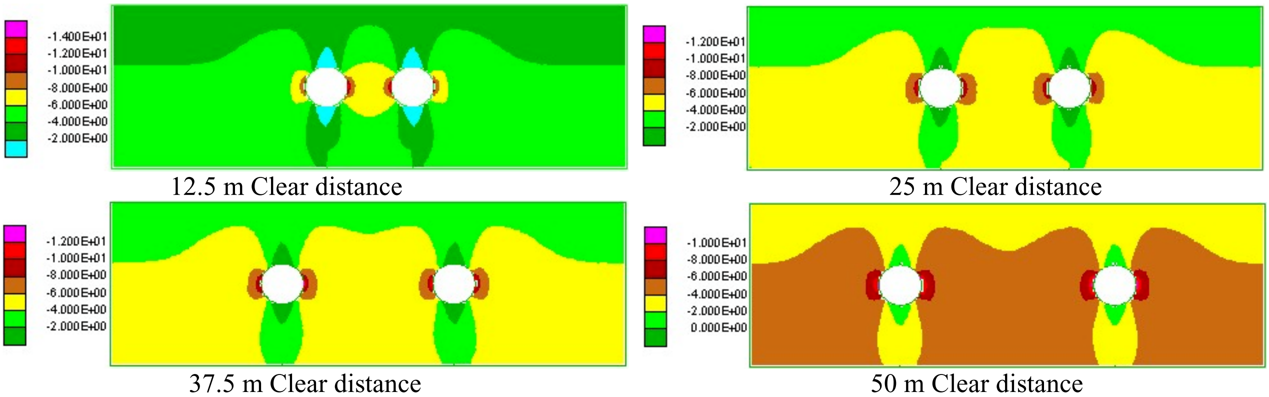

Figure 6. Major Principal Stress Contours for 12.5 m diameter tunnels (Empty)

A critical study of the stress distribution around the tunnel system leads to a general conclusion that as the spacing between the tunnels increases, the stress distribution on the inner and outer side of the tunnel more or less tends to become identical, especially at a spacing of 4D. This implies that when the tunnels are in close proximity to each other there is interaction between them which results in unequal stress distribution on both the spring lines. This interaction decreases as the spacing between the tunnels increases. The detailed analysis of the pressurized tunnels indicates that, with the increases in internal pressure, the difference in the measured stresses at the inner and outer spring lines increases, the phenomenon being more pronounced when the tunnel spacing is less. The minor principal stress contours also indicates that there is virtually no interaction between the tunnels at a spacing of 4D. Since the response of the tunnels is similar irrespective of their diameter, the major principal stresses contours, X-displacement contours and Y – displacement contours of the 10 m diameter tunnels only are presented in this paper as Figures 7 to 15.

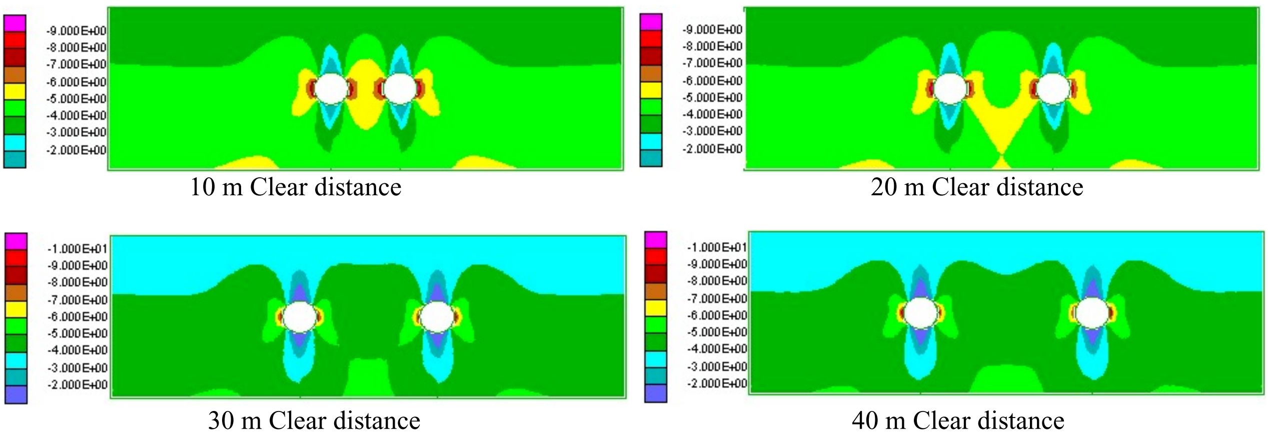

Figure 7. Major Principal Stress Contours for 10 m diameter tunnels (Internal Pressure 1.5 MPa)

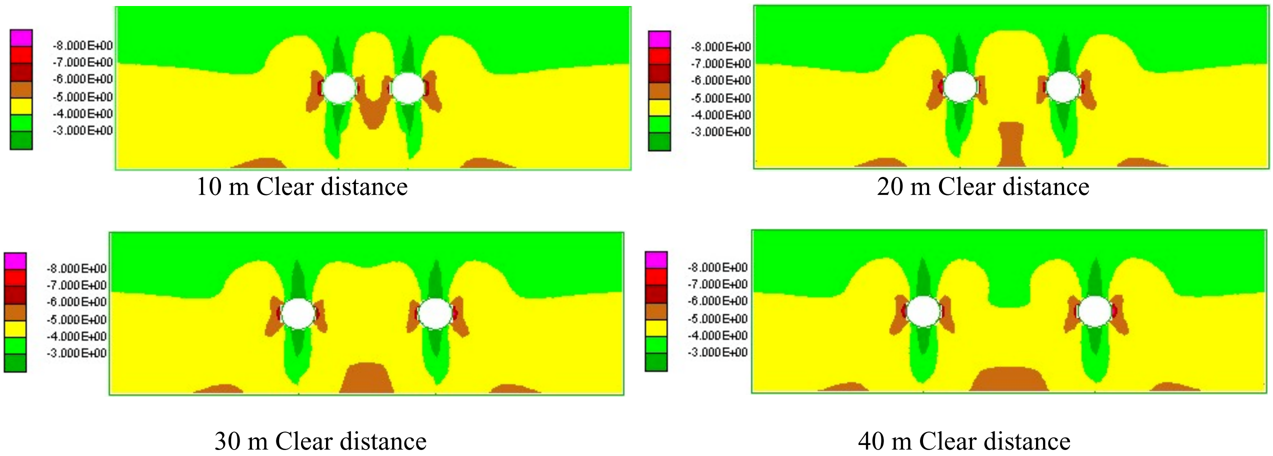

Figure 8. Major Principal Stress Contours for 10 m diameter tunnels (Internal Pressure 3.0 MPa)

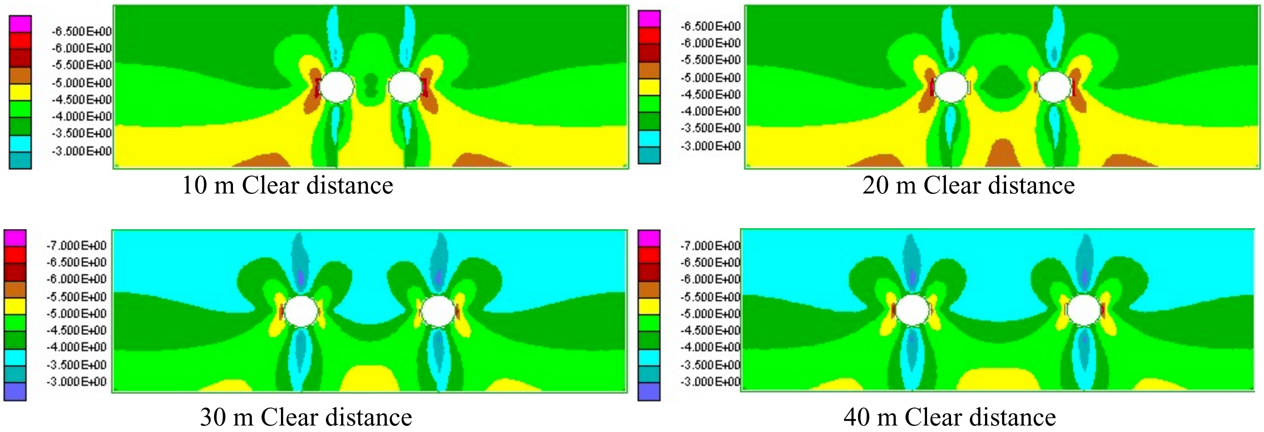

Figure 9. Major Principal Stress Contours for 10 m diameter tunnels (Internal Pressure 4.5 MPa)

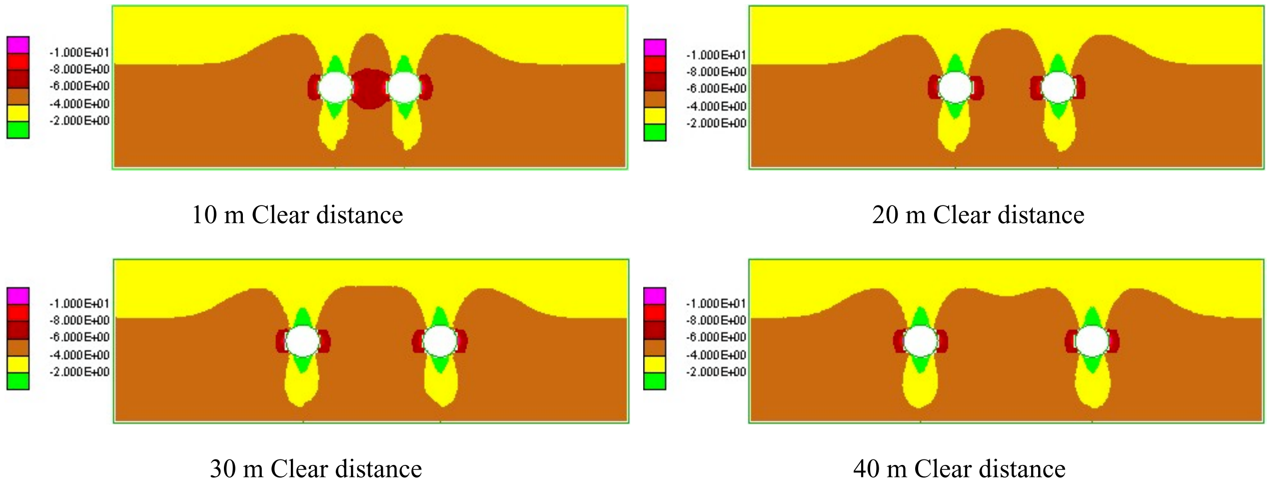

Figure 10. X – Displacement Contours for 10 m diameter tunnels (Empty)

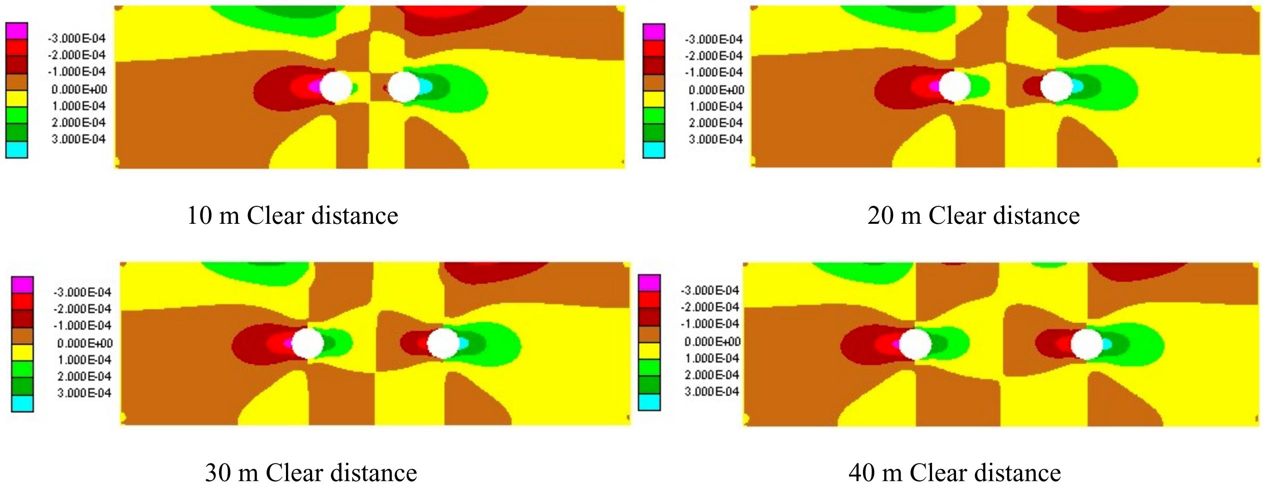

Figure 11. X – Displacement Contours for 10 m diameter tunnels (Internal Pressure 1.5 MPa)

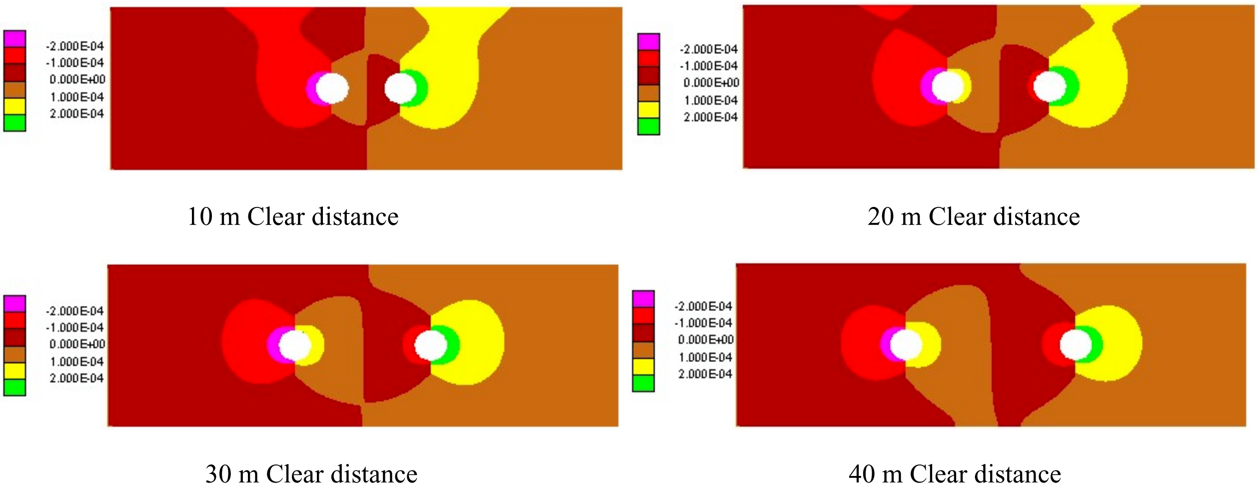

Figure 12. X – Displacement Contours for 10 m diameter tunnels (Internal Pressure 3.0 MPa)

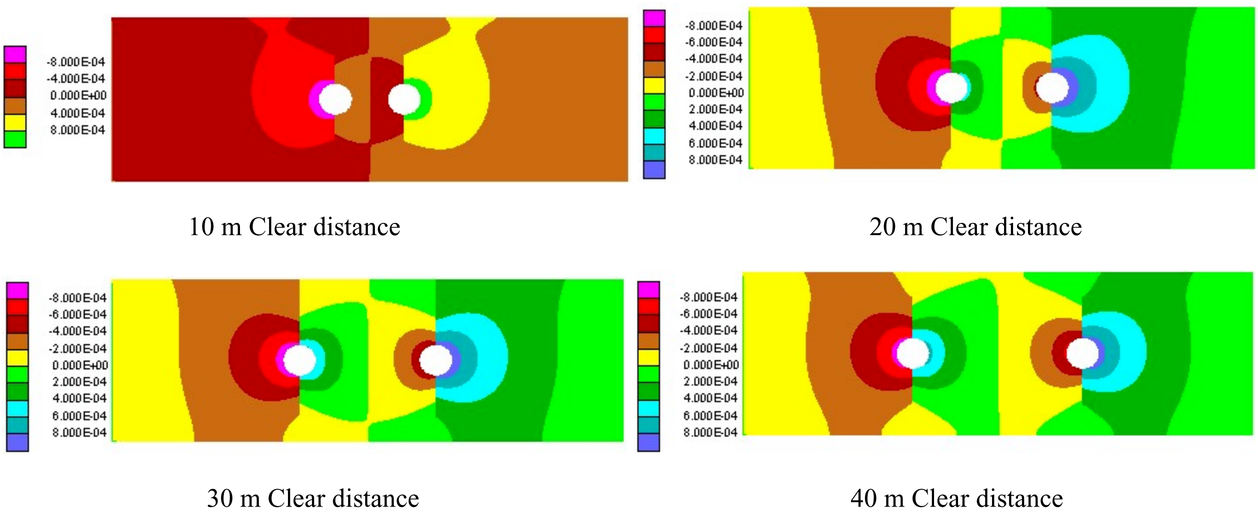

Figure 13. X – Displacement Contours for 10 m diameter tunnels (Internal Pressure 4.5 MPa)

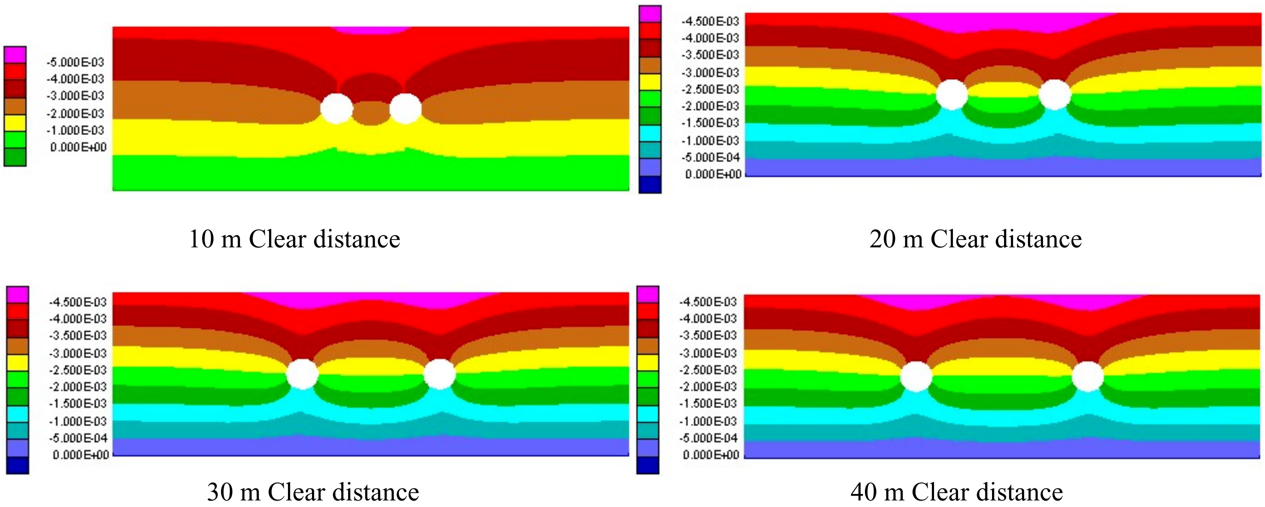

Figure 14. Y – Displacement Contours for 10 m diameter tunnels (Empty)

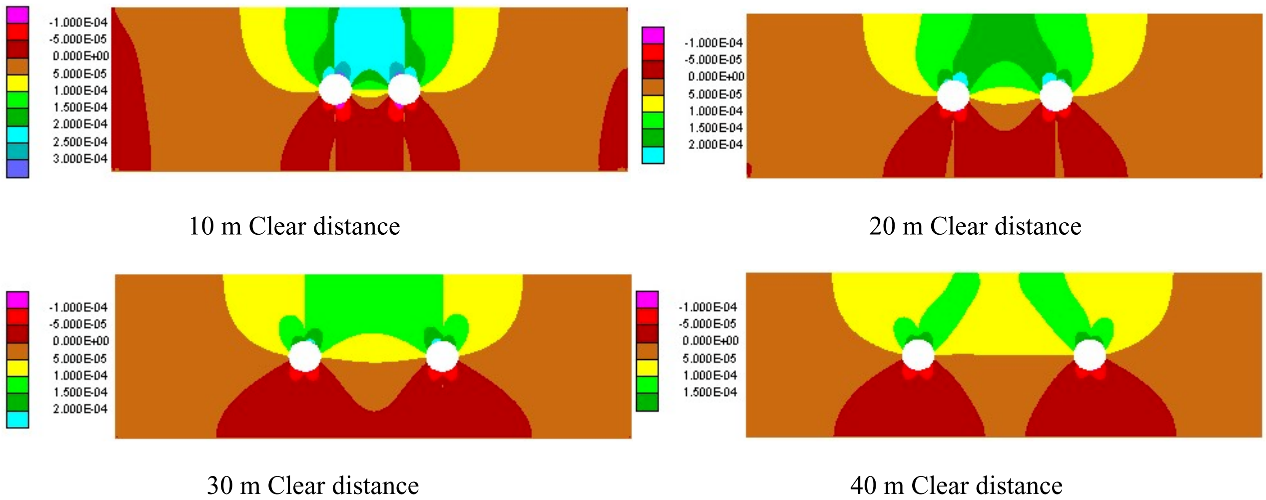

Figure 15. Y – Displacement Contours for 10 m diameter tunnels (Internal Pressure 1.5 MPa)

Apart from the stress distribution around the tunnels, another parameter which is an indicator of the influence of tunnels on each other is the deformation at the spring lines and more precisely the deformation in the horizontal direction. The X-displacement contours indicate that as the spacing between the tunnels increases, the displacement contours on the inner and outer side of the tunnel more or less tend to become similar both in extent and magnitude. The trend appears to be the same in the case of an empty tunnel and of a pressurized tunnel. In order to understand this phenomenon more precisely the deformations at both the outer and inner spring lines have been tabulated in Table 1, for the case of an empty tunnel.

It may be noted from the table that the percentage variation in the values of the x-displacements of the tunnels spaced at 1D and 2D is 30 %. As the spacing increases from 1D to 4D, the percentage variations also increases from 30% to 55%, 70% and 81% respectively. It may also be noted that the difference in the size of the tunnels does not appear to have any major influence on the behaviour of the tunnels. The increase in the diameter of the tunnels results in a slight increase in the x-displacement only. However, it would be premature to state that the size of the tunnel does not have any influence on the interaction of the tunnels. A detailed analysis is required to be carried out to confirm this behaviour. The graphical representation of the clear distance and the X-displacement presented in Figure 16 clearly indicates the effect of clear distances between the tunnels on X-displacements at the Spring Lines in the case of unpressurized (empty) tunnels. Figure 17 indicates the effect of the tunnel size on the interaction between the twin tunnels.

Table 1. Major Principal Stresses and X-Displacements at the spring lines of Empty Tunnel.

Tunnel Diameter m	Spacing m		Major Principal Stress, MPa		X - Displacement, mm	
			Outer	Inner	Outer	Inner
7.5	1 D	7.5	13.820	13.200	0.257	0.079
	2 D	15	13.360	12.660	0.249	0.139
	3 D	22.5	12.400	12.070	0.239	0.167
	4 D	30	13.260	12.710	0.237	0.192
10	1 D	10	13.540	14.000	0.347	0.106
	2 D	20	13.290	13.430	0.334	0.190
	3 D	30	13.030	13.000	0.321	0.237
	4 D	40	13.010	13.110	0.317	0.268
12.5	1 D	12.5	14.050	14.080	0.429	0.135
	2 D	25	13.580	13.410	0.407	0.247
	3 D	37.5	13.700	13.390	0.394	0.311
	4 D	50	13.520	13.510	0.381	0.346

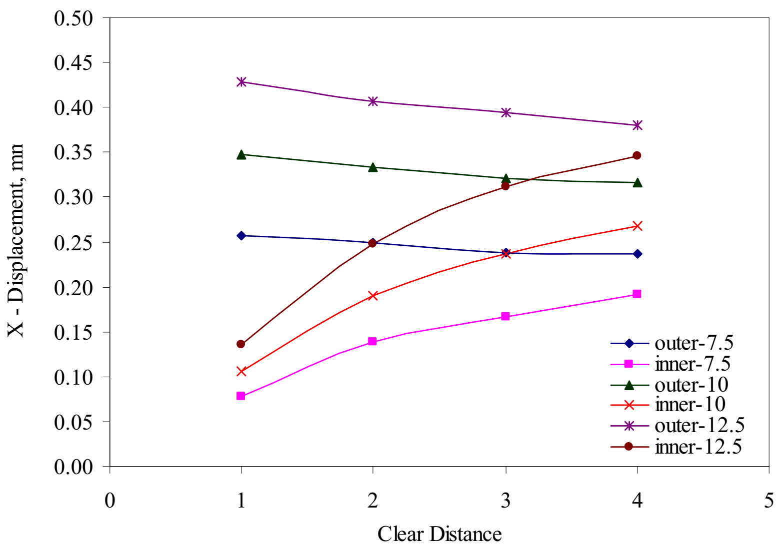

Figure 16. Effect of Clear Distances between the tunnels on X-displacements at the Spring Lines

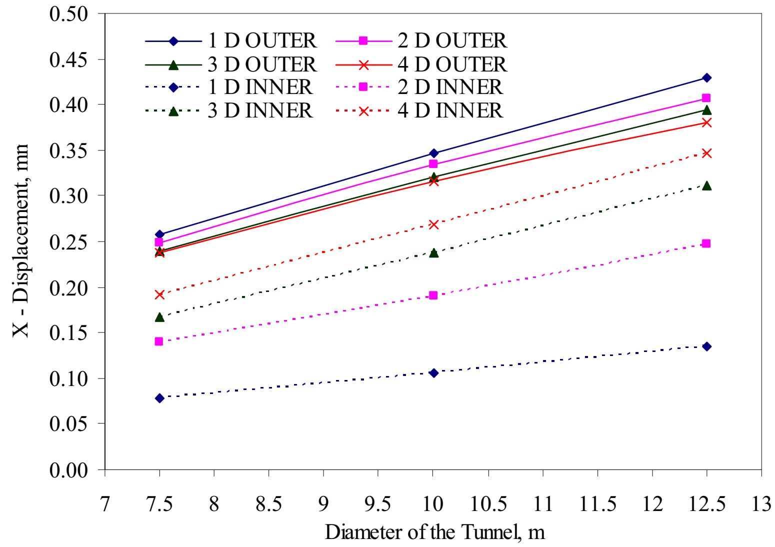

Figure 17. Effect of size of the tunnels on the interference of the twin tunnels

CONCLUSIONS

From the analysis of the twin circular tunnels, the following conclusions can be drawn:

- As the internal pressure increases, the zone of higher major principal stresses at the crown increases and at the springing level decreases.
- The major principal stresses are maximum at the crown and the invert of the tunnel. Therefore, these positions of the tunnel have to be critically examined for designing LPG Storage Caverns.
- Taking the major principal stresses at the crown and the invert level as the deciding criteria, the minimum critical distance to be maintained between twin circular tunnels should be 4D for invalidating the effect of interference of tunnels.
- Generally, the increase in internal gas pressure of the tunnel increases the X-displacement at the crown and springing levels.
- The displacements at the crown in the x-direction indicate that the minimum critical distance to be maintained between twin circular tunnels should be 3D for invalidating the effect of interference of tunnels.
- The increase in internal gas pressure of the tunnel decreases the Y-displacement at the crown and springing levels.
- The displacements at both the springing levels indicate that the minimum critical distance to be maintained between twin circular tunnels should be 4D for invalidating the effect of interference of tunnels.

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