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Research Article

Numerical modelling of concrete tunnels exposed to rock fall

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Abstract: Tunnel entrances are among the most likely places for rock fall events. For this reason, concrete tubes are constructed before tunnel entrances against rock falls. In this study, the normal stress and the deformation in both horizontal and vertical directions occurred by crashing rock on concrete tunnel tubes were investigated using finite element method in three dimensional conditions. Different velocities and masses of falling rock analyzed to demonstrate effect of velocity on normal stress and deformations. It was observed that deformations on the concrete tube increased as the impact energy increased due to increasing velocity and mass. The mass of crashed rock, M, is changes from 3 kN to 200 kN and peak deformations could reach approximately 150 cm when the mass of falling rock was M=200 kN and V = 30 m/s. When the velocity of rock V=10 m/s just before the impact, the ratios of deformations to rock mass of 3 kN, 25 kN, and 200 kN were approximately 0.00066 m/kN, 0.0014 m/kN and 0.00175 m/kN, respectively.

Keywords: Concrete tubes, finite elements, numerical analysis, rock crashing, impact energy.

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1. Introduction

In recent years many engineering structures such as bridges, buildings, roads, dams, tunnels etc. have been exposed to rock fall. The increase of the earthquakes and the effect of freezing-thawing cause an increment of the rock fall events. In areas under the risk of rock fall, while engineering structures are designed, rock fall must be considered in calculations and necessary precautions should be taken. Numerical studies are of great importance in engineering designs that can be constructed in areas where there is a risk of rock fall, to predict the deformations that may be caused by rock fall (Altay 2015, Altay and Kayadelen 2015). It is crucial to know the deformations and stresses caused by rock falls in order to make the designs more economical. A European Union country, Switzerland, spent 6.7 million dollars annually for protecting civil engineering structures from rock falls (Grassl et al. 2002). In different parts of the world, rock fall events also occur frequently. One of the engineering structures that is at risk of being damaged by rock falls is concrete tubes built at tunnel entrances. The tunnels are needed to build in mountainous region and tunnel entrances are places where the rock fall risk is higher than other structures. Due to crashing the rock, the concrete tubes may collapse and therefore infrastructures and vehicles on the road can be damaged. Fig. 1. shows an example of rockfall event at a tunnel entrance. It is obvious from the Fig.1. that the falling rocks can result in human deaths.

Normally the designs are considered by examining the equilibrium state of the concrete structures. The impact forces created by the rock falls and the reaction of the structures against them play a key role in the design of these types of structures.

Some studies have been conducted in the literature for the formulation of the relationship between the impact force and the design parameters of the structure (Pichler et al. 2005; Wang et al. 2012). Although some studies involve the analysis of concrete tubes under seismic influences or earthquakes. Studies in the literature about design of concrete tubes under rock crash that creates the dynamic effects are still inadequate.

Figure 1. An example of rock fall event occurred on concrete tube (Hu et al. 2018).

In the studies concerned with rock crash to different structure such as bridge, embankment, it is made use of following methods which are the shear strength reduction finite element method (SSRFEM), limit equilibrium methods (LEM), numerical approaches and limit analysis. SSRFEM has been traditionally preferred to achieve damage estimation of engineering structures. But according to many researchers SSRFEM has some disadvantages due to complexity and hard to understand (Chen et al. 2014, Shi and Goodman 1985). Although it is poor with respect to stress and strain distribution in structures, LEM is either efficient or easy understood for the solution of failure mechanism (Terzaghi, 1950). A study on SSRFEM was carried out by Chen et al. (2014). They produce a solution taking account effects of rigid rotation on undeformed slope. The other method called discontinuous deformation analysis was suggested by Shi and Goodman (1985). It offers to calculate the translation, rotation and deformation of a slope as 3D analysis.

One of the most important problems in rock falls is to estimate the impact force that occurs at the time of impact. Labiouse et al. (1966) performed an experimental study to understand impact action mechanism by presenting a mathematical expression which predicts the impact force. They also investigated the usage of cushion to obtain the damping. It was reported that the results of the experiments were compatible with the ones they found from the equation they proposed. Their equation (Eq. 1) is given below:

$$P_{max} = 1.765 M_E^{\frac{2}{5}} R^{\frac{1}{5}} \left(MH^{\frac{3}{5}}\right)/1000 \quad \text{Labiouse et al. (1966)} \tag{1}$$

where; P_{max} is maximum impact force, M_E is Elastic modulus of cushion layer (kPa), R is the equivalent radius of rock fall (m), H is falling height (m).

Calvetti et al. (2005) proposed an equation (Eq. 2) for the force of impact by performing both experimental and numerical studies. According to them, the maximum force at the moment of impact for the rock falling on the granular layer depending on the impact energy can be expressed as follows:

$$F = F_o\left(\frac{E_i}{E_{i0}}\right)^{2/3} \quad \text{Calvetti et al. (2005)} \tag{2}$$

where F_o is impact force corresponding to impact energy (E_{i0}).

Japan Road Association (2000) proposed an equation (Eq. 3) which is derived an elastic contact theory to calculate impact force on a sand cushion caused by a rock fall. This equation given below was used to design of rock fall prevention cover.

$$P=2.108(mg)^{2/3}\lambda^{2/5}H^{3/5} \quad \text{Japan Road Association (2000)} \tag{3}$$

where P: impact force [kN], m: rock weight [t], g: earth gravity [9.8 m/s^2], λ is Lame´s constant of a sand cushion [kN/m^2] and H is the height of a drop [m].

Chu and Zhang (2011) studied on model experiments in the laboratory to estimate impact effects and impact force if a ship hits the bridge foundation. In the experiments they conducted, it was stated that the front surface geometry and speed of the ship were effective parameters on the effects of the crash. They proposed the empirical correlation (Eq. 4) below to estimate the impact force from the experimental data obtained.

$$P = \alpha\eta(DWT)^{0.43}v^{1.27}m^{0.09} \quad \text{(Chu and Zhang, 2011)} \tag{4}$$

where; α=The coefficient of pile group size, , η=The coffecient of ship structural (for a buffer bow η=0.12 or for a stiff bow η=0.58), *DWT*= ship tonnage (t), *v*= impact speed (m/s), m=dead weigth of the bridge (t).

Another study for the prediction of impact force in rock falls has been done by Yu et al. (2018). In their experimental study, they used balls that made of iron, granite and wood, which simulate the rock block at different angles, to hit a wall. They conducted experiments at different crash angles with the balls which have different velocities. Under these conditions the impact force was measured. Yu et al. (2018) developed the equations 5 and 6 for maximum impact force (F) proposed by Buckingham (1915) using the data obtained from their experimental studies as follows:

$$F=0.35(EE_k^2)^{1/3}(\sin\alpha)^{0.5} \quad \text{Yu et al. (2018)} \tag{5}$$

$$E = \frac{E_1E_2}{E_1+2E_2} \quad \text{Yu et al. (2018)} \tag{6}$$

In this equation, E can be taken as equal to E_2 when E_1 is far larger than E_2. If a cushion layer is used, the difference will be huge between elastic modulus of rock (E_1) and elastic modulus of rock (E_2). For that results, elastic modulus of rock (E_1) can be ignored, so E_2 may have a dominant component on impact force.

Zaid et al. (2020) and Zaid (2021a) studied on the deformations caused by impact on rock tunnels. For this purpose, the author tried to understand the deformation behavior of tunnels by using numerical simulations. According to the results of numerical simulations the unconfined compressive strength of the rock had great importance on deformation behaviors. Zaid (2021b) also modelled a missile crashing onto the reinforced concrete tunnel constructed in rock by using numerical program. In this study the weathering of the rock also was taken into consideration in numerical models. The results of numerical analysis showed that the weight of missile and weathering of rock had crucial importance on tension and compression damage of tunnel. The weathering effect during blasts also was studied by Mishra et al. (2021), Zaid (2021c) and Zaid et al. (2022). Similarly, it was concluded that from those studies that the weathering issue effected the deformations on the tunnel significantly. The effect of blast loading on deformations of rock tunnels was also investigated by Sadique et al. (2022) and Zaid and Shah (2021). It can be deduced from those studies that the deformation response of the tunnels strongly depends on the types of surrounding rocks.

Numerical studies are of great importance in engineering designs that can be constructed in areas where there is a risk of rock fall, to predict the deformations that may be caused by rock fall. It is crucial to know the deformations and stresses caused by rock falls in order to make the designs more economical. This study is of great importance in terms of predicting the deformations that may occur in tunnel designs. For this reason, this manuscript is focused directly on the behavior of concrete tube exposed to rock impact. Three-dimensional numerical analyses have been carried out to observe maximum deformation on the concrete tube with the help of ANSYS program that uses finite element method. The numerical analyses were performed in three dimensions with different parameters. The change in maximum deformation and occurred normal stress are investigated by the change in velocity and impact energy of rock block.

2. Numerical analysis

One of the 3D programs, ANSYS, based on finite element analyses was used to conduct the numerical analyses. Explicit dynamics analysis system was chosen in ANSYS workbench. The concrete blocks were used in model to represent falling rocks in analyses. Then geometry of concrete tube and falling rock was created with design modeler plugin as shown in Figure 2.

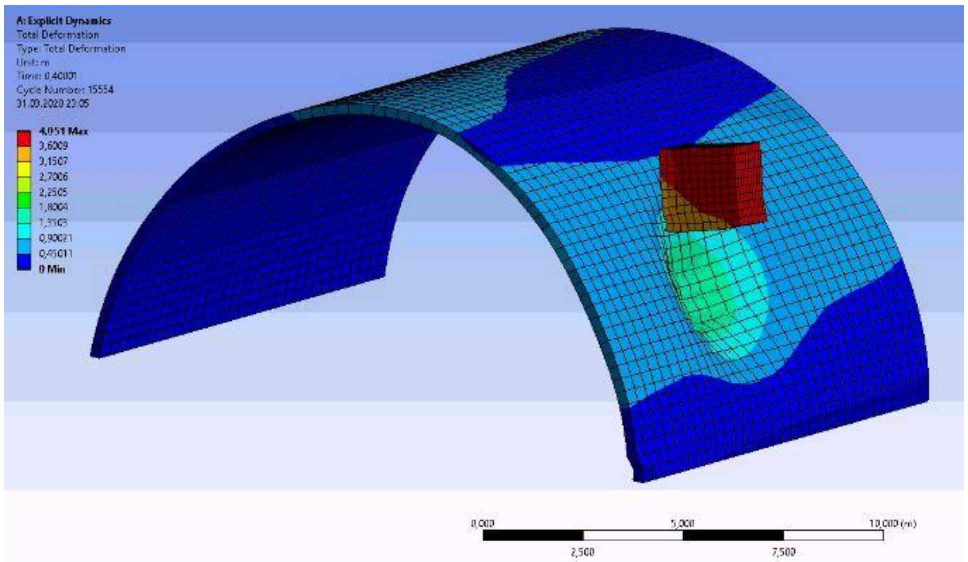

Figure 2. Rock impact simulation in ANSYS program.

Concrete tube's radius is 7 m. Two different tube cross-section thicknesses (t), 25 cm and 30 cm are selected. Grid steel reinforcement applied with steel bars that have diameters of 10 mm is used for the concrete tube. The model can be seen from Figure 2. The material properties of concrete used for concrete tube and crashing rock and steel used for concrete tube reinforcement are presented in Table 1. and Table 2. respectively.

Table 1. Parameters of concrete used for the falling rock block and concrete tube.

Properties	Units	Values
Mass density	kg/m^3	2400
Young's modulus	MPa	31.000
Poisson's ratio	−	0,19
Bulk modulus	MPa	16667
Shear modulus	MPa	13025

Table 2. Parameters of steel bars used for concrete tube reinforcement.

Properties	Units	Values
Mass density	kg/m^3	7800
Young's modulus	MPa	220.000
Poisson's ratio	−	0,31
Bulk modulus	MPa	192980
Shear modulus	MPa	83969

In analysis, the behavior of the concrete tube was studied for different velocities of falling rock, different rock sizes and different tube cross-section thickness. Firstly, change in normal stress occurred on the impact area is analyzed with the change in velocity of falling rock blocks in terms of max impact stress, max duration time and time to reach the peak impact stress. In second part, analysis performed to observe maximum deformation changes in vertical and horizontal directions. In the third part another important parameter, the impact points on concrete tube, is investigated to examine the max deformation changes. Numerical analysis cases for all rock impact are given in Table 3. Analyses examined are in three cases that A, B and C. Each case also has three subgroups to make analyses results more apparent.

Table 3. Numerical analysis cases for all rock impact.

t=25(cm)	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-1	C-3
t=30 (cm)	X-1	X-2	X-3	Y-1	Y-2	Y-3	Z-1	Z-2	Z-3
M (kN)	3	3	3	25	25	25	200	200	200
V (m/s)	10	20	30	10	20	30	10	20	30

Tube thickness=t (cm) Velocity=V (m/s) Rock Weight=M (kN)

2.1. *The effect of rock velocities*

Analyses were examined in three different cases that was given in Table 3. Figures 3-5 shows the change of deformations that occur during the impact of rock masses with different velocities. For all the different rock masses used in the analysis, it is clearly seen that the deformations increase with increasing rock velocity significantly. This shows that rock velocity is a dominant parameter on deformations. Peak deformations for M=3 kN, 25 kN and 200 kN of concrete blocks when V = 30 m/s are approximately 1 cm, 12 cm and 150 cm, respectively. In case C analysis, where the weight of the rock is 200 kN, it is understood that the deformation is very high, that is, the concrete tube completely collapses. The time to reach peak deformations in large mass rock collisions is greater according to the smaller rock blocks. For example, while peak deformation for the analysis of case A occurs about at 20 ms, this value is approximately 200 ms in the case C. In all three cases (A, B, C), when the velocity increases from 20 m/s to 30 m/s, peak deformation values increase almost by 50 percent. However, when the velocity rises from 10 m/s to 20 m/s, the peak deformation values increase more than twice.

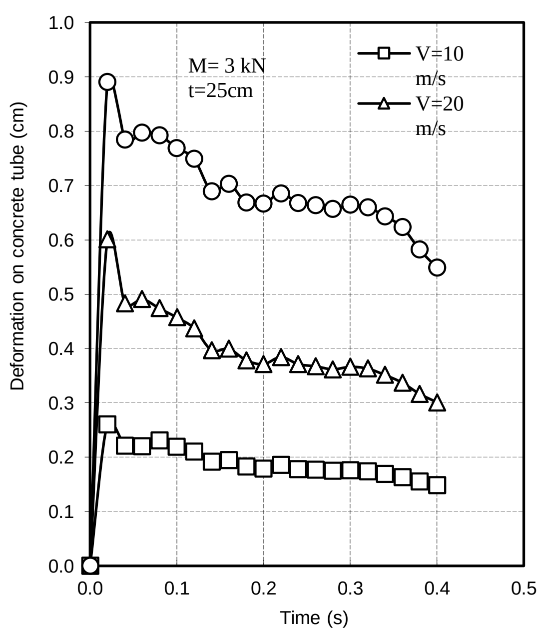

Figure 3. Time history of deformation of A cases.

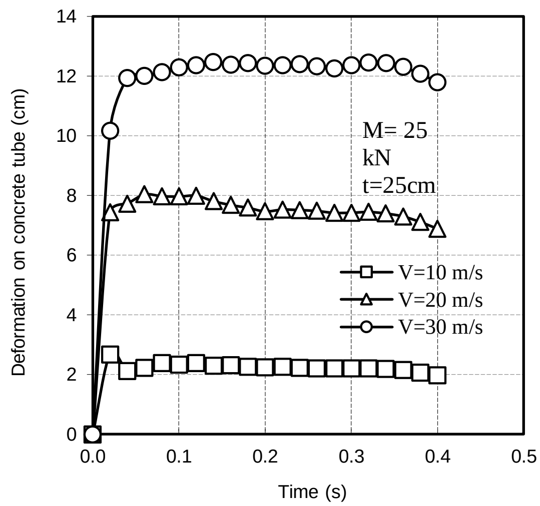

Figure 4. Time history of deformation of B cases.

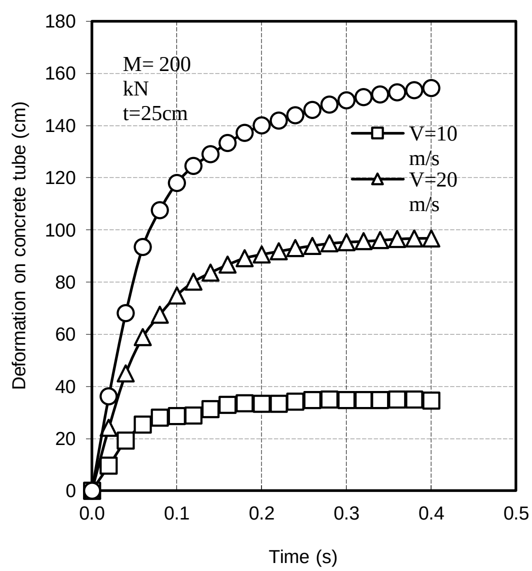

Figure 5. Time history of deformation of C cases.

2.2. *The effect of rock mass and impact energy*

In order to realize the effect of rock mass on deformations in concrete tube, analysis results with the same parameters were compared in Figures 6-8. The mass of the rock, M, varies from 3 kN to 200 kN, while the volume of it changes about 64 times with this variation. For all cases, impact point on concrete tube is the same (impact point is 3.5 m above ground-level), while crashing rock velocities are different such as V=10, 20 and 30 m/s. The effect of rock mass on the deformations can be clearly seen in three graphs. As in the C cases analysis, when the rock mass becomes too large, it shows a significant increase in deformations compared to other cases. For V=10 m/s, ratios of deformations to mass of A, B and C cases in terms of m/kN are approximately 0.00066, 0.0014 and 0.00175, respectively. It is seen that there is a 2.65 times difference between the effect of 3 kN rock impact and the effect of 200 kN rock impact. Undoubtedly, we can conclude that rock mass is one of the important parameters on impact deformations.

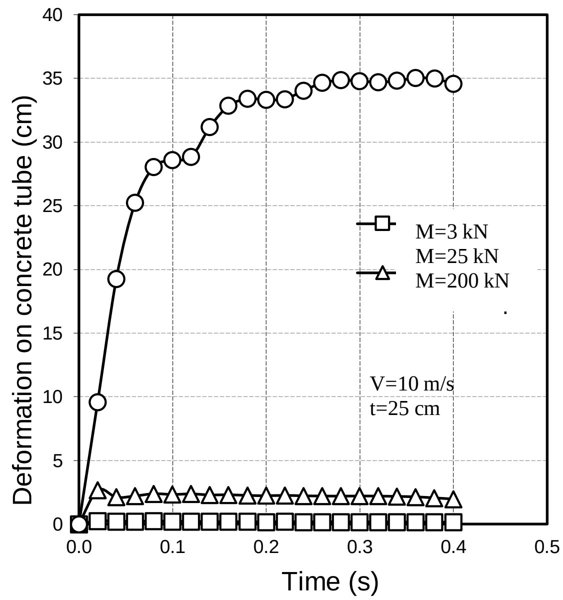

Figure 6. Effect of rock mass on deformations for V=10m/s.

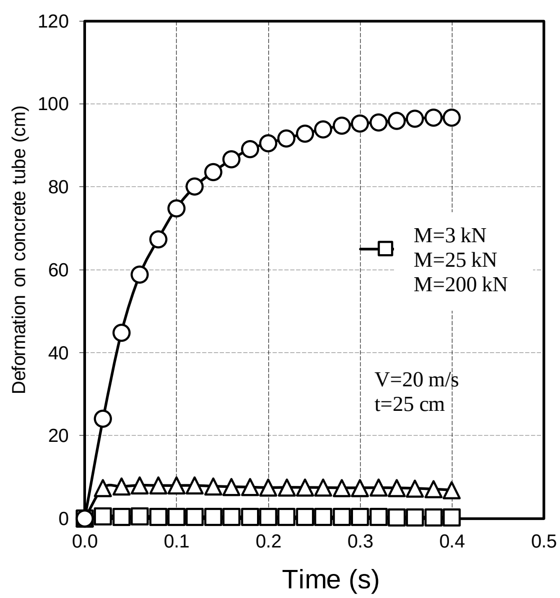

Figure 7. Effect of rock mass on deformations for V=20m/s.

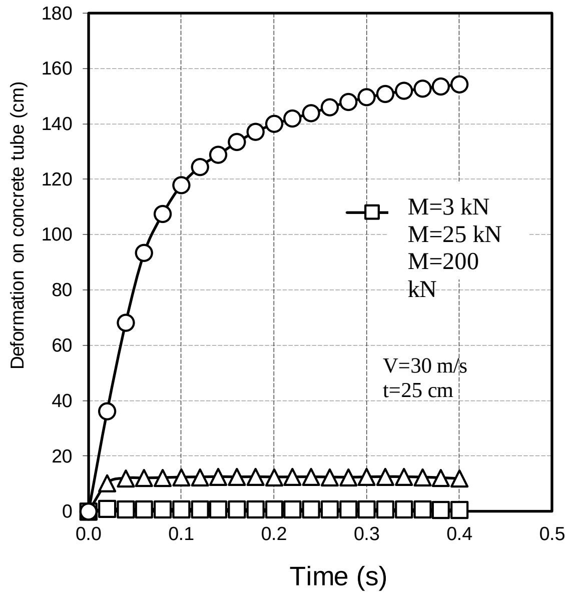

Figure 8. Effect of rock mass on deformations for V=30m/s.

Definitely, it would be the most appropriate way to evaluate the effect of the impact energy of the rock mass on the deformations in order to reflect the effect of mass and velocity together. Therefore, the changes of deformations with the energy are depicted in Figure 9-11. In this graph, changes are presented for two different concrete tube thicknesses together, i.e., t=25 cm and t=30 cm. For V=10 m/s, the ratios of deformations to impact energy of A, B and C cases in terms of m/kN are 0.00013, 0.00017 and 0.00016, respectively. The ratios of deformations to impact energy are close to each other when you consider the difference between impact energies. On the other hand, the increase in the thickness of the concrete tube has a positive effect on the deformations, leading to deformations reduction. It caused an average decrease of 27 % in deformations in 3 kN rock impact. This decrease is 53 percent on average in B and C cases. From Figure 9-11 it can be obviously seen that the difference in maximum deformation increases with impact energy for both thicknesses.

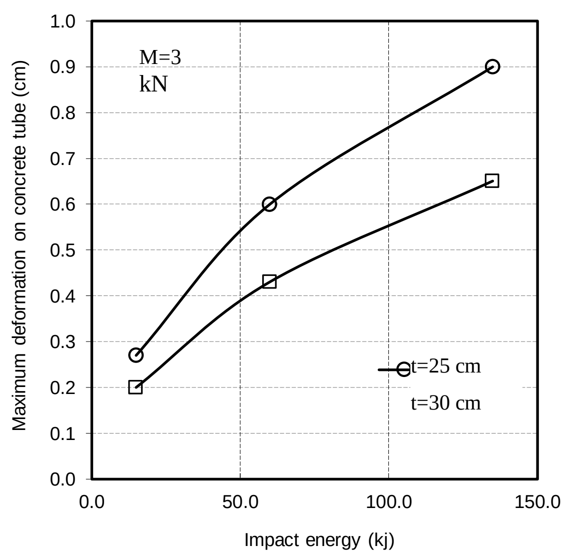

Figure 9. Variation of deformations with impact energy for M=3 kN.

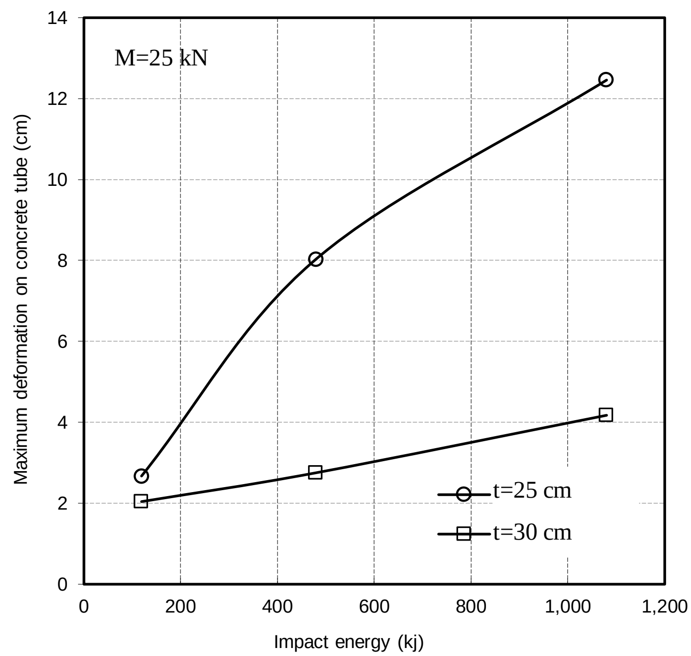

Figure 10. Variation of deformations with impact energy for M=25 kN.

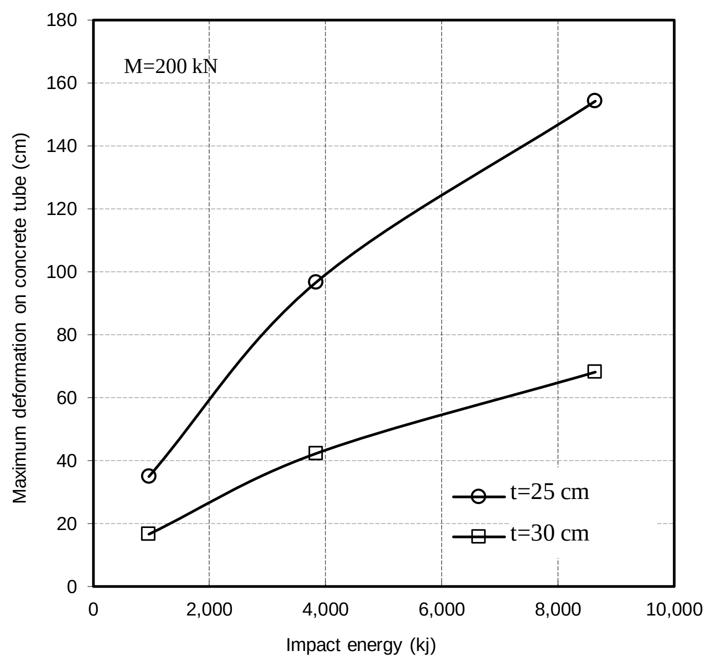

Figure 11. Variation of deformations with impact energy for M=200 kN.

2.3. *Impact stress*

There is a strong relationship between dynamic response of structures and time to reach the peak impact stress. Longer time leads lower stress capacity of concrete structures. Therefore, time history of impact stress is substantial and challenging process to interpretation the dynamic response of the concrete tube. It was reported that the greatest damage occurred onto the impact surface in rock crash events (Lu and Zhang 2011). For this reason, vertical impact direction has been applied in order to obtain the most negative condition. Thus, the effect of rock mass and rock velocity on impact damage was emphasized. Figures 12-14 show the time history of impact stress. When Fig. 12. is examined for rock mass equals to 3 kN, the time to reach the peak impact stress is about 20 ms for all velocities. The maximum impact stresses are 1500 kPa, 1030 kPa and 660 kPa in V=10, 20 and 30 m/s, respectively. It is clear that the velocity of the rock has a significant effect on the impact stress, while it does not have a remarkable effect on the duration of the impact. It is possible to say a similar phenomenon for other dimensional rock impact analysis.

The time to reach the peak impact stress for heavier rocks appears approximately the same, i.e., 20 ms on Fig. 13. and Fig. 14. However, a noticeably increase in the impact stress is observed, as the rock weight increases. A different trend is seen on the impact stress in Fig 14. when compared with Fig. 12 and Fig. 13 by the change in velocity. The analysis performed for V=10, 20 and 30 m/s and M= 200 kN shows that the impact stress are close to each other. This behavior can be explained as the impact stress cannot reach higher values due to the large volume of collapse on the concrete tube even the large rock block crashes. It can also be said that the very rapid occurrence of the collapse has an effect on this behavior. We can understand this situation if we examine the curves in Fig.5 which shows the time history of the deformations for 200 kN of rock mass, that deformations can reach great values as the velocity increases.

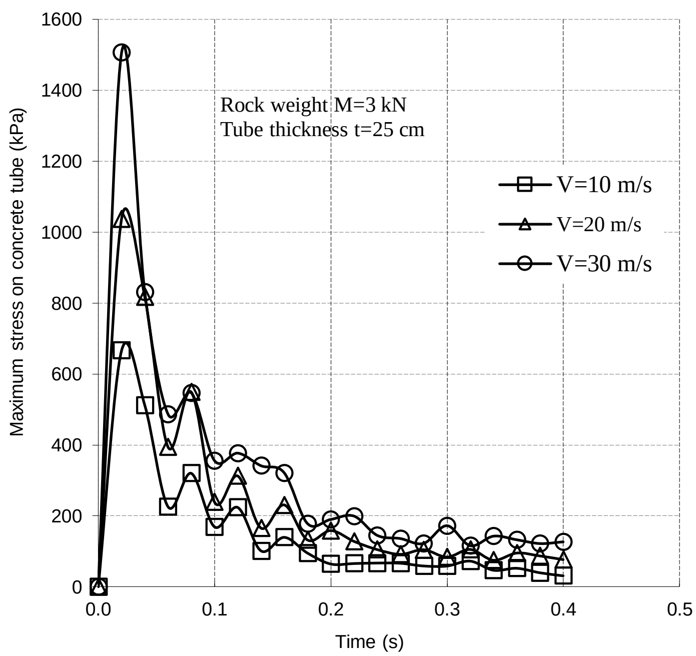

Figure 12. Time history of maximum stress on concrete tube for M=3 kN.

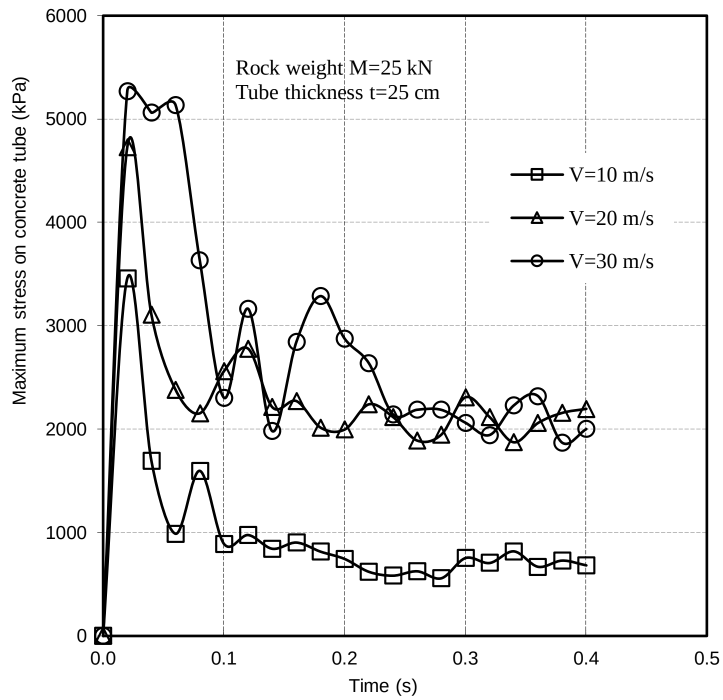

Figure 13. Time history of maximum stress on concrete tube for M=25 kN

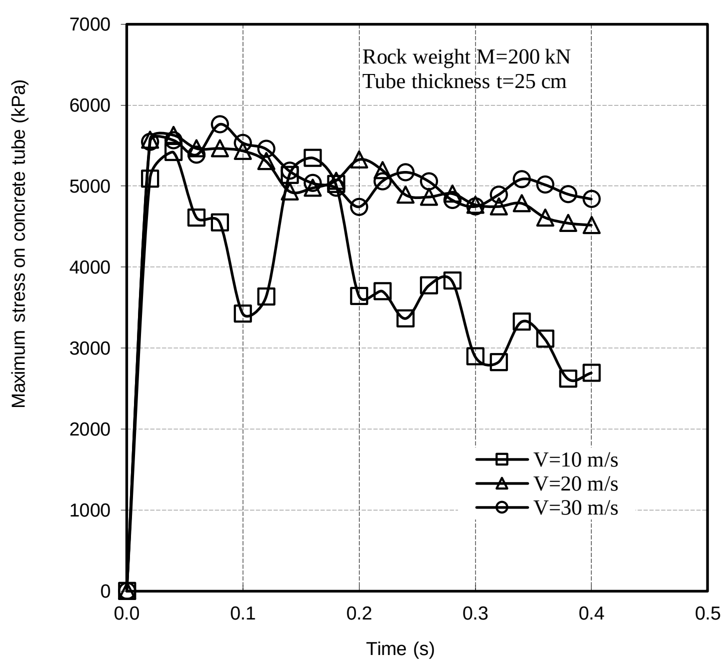

Figure 14. Time history of maximum stress on concrete tube for M=200 kN.

3. Conclusions

This study presented a three-dimensional numerical analysis for the behavior of concrete tube exposed to rock impact. The simulation using finite element method has been carried out in order to observe maximum deformation and stresses on the concrete tube. In the simulation the effects of different parameters causing damages on concrete tube have been focused. The change in maximum deformation and occurred normal stress have been investigated by the changes in velocity, impact energy and rock mass. It is possible to summarize the findings obtained in this study as follows:

1. Numerical simulations have shown that the rock impact can cause serious deformation on concrete tube, when the rock mass is larger than 3 kN. Rock mass of 200 kN leads completely collapse of the concrete tube;
2. The rock velocity and rock mass are the dominant parameters on deformations. Peak deformations can approximately reach 150 cm when M=200 kN. and V = 30 m/s. For case C analysis, where the weight of the rock is 200 kN, we can conclude that the deformation is very high, that is, the concrete tube completely collapses. The time to reach peak deformations is affected by rock velocity;
3. The mass of crashed rock, M, is changes from 3 kN to 200 kN, seems one of the important parameters on impact deformations. The ratios of deformations to rock mass of A, B and C cases when V=10 m/s are approximately 0.00066, 0.0014 and 0.00175 m/kN respectively;
4. Interpreting of the effect of the impact energy of the rock mass on the deformations is more convenient approach. The ratios of deformations to impact energy of A, B and C cases are close to each other which are 0.00013, 0.00017 and 0.00016 m/kN, respectively, when V=10 m/s;
5. The increase in the thickness of the concrete tube provides an affirmative effect on the deformations. 20 % increase in concrete tube thickness causes an average decrease of 27 % in deformations for 3 kN rock impact. This decrease is 53 percent on average in B and C cases;
6. The dynamic response of the structures is related to the time to reach the peak impact stress, duration and maximum impact stress. For A and B cases, time to reach the peak impact stress are close to each other and about 20 ms for all rock velocities. The maximum impact stresses are 1500 kPa., 1030 kPa. and 660 kPa. Due to the very rapid occurrence of the collapse because of high velocity and large mass, the impact stresses cannot reach to their real maximum values.

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