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Journal on Civil Engineering

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Journal on Civil Engineering

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EDITORIAL

Greetings to all researchers, academicians, librarians, and other readers!

The history of Civil Engineering is linked to knowledge of structures, materials science, geography, geology, soils, hydrology, environment, mechanics and other fields. The current issue presents nine interesting topics.

Amin Zoratipour and his co-author Marjan Firoozy Nejad have presented a study about investigating the urban industrialization and the creation of heat islands. The authors have studied the land use and temperature changes and Landsat 8 satellite images were used for the years 1991 and 2016 at the beginning and end of a 25-year period. To reprocessing, Support Vector Machine (SVM) classification and Vegetation Index (NDVI) were applied. The results showed that on average, real and estimated temperatures increased by 3.7 and 4.52 °C during the period, respectively. Also, the Root Mean Square Error (RMSE) (1.26) represents an incremental direct relationship between industrialization and Land Surface Temperature (LST).

Rekha Singh and co-author Sanjay Goel have investigated the durability properties of the pervious concrete mixture, as porosity with an interconnected network of pores causes a significant decrease in its strength and resistance against chemical and physical attacks. Durability tests in the laboratory were performed to judge the performance of pervious concrete made by blending cement containing limestone powder, silica fume, and metakaolin and the testing program includes abrasion, sulphate, and acid resistance. The results of this study are based on mass loss measurement and to understand the pattern of acid and sulphate attack in pervious concrete, SCMs are used as cement replacement by using different parameters and factors.

Srinivasa Kumar et al. have performed a study as a performance evaluation of toll plazas using queuing theory. This research has focused on to determine the performance evaluation of a few electronic toll collection and manual toll collection gates on National Highway (NH) 65 and Outer Ring Road. The arrival rate, service rate, delays, and the queue length data were collected. The results showed that, the arrival rates were input into a passion distribution based queuing model to determine the performance parameters of toll plazas and also the required number of servers at the study plazas.

Janhabi Meher has presented a study about missing discharge data filling with artificial neural network. In this study, artificial neural network is applied to fill in missing discharge data from nineteen discharge stations of Mahanadi river basin located at Chhattisgarh and Odisha in India for the five monsoon months (June - October). The input data selection method applied in this study was using data as input having 2 good correlation coefficients with target data. The coefficient of determination (R2) between observed discharge and predicted discharge for the nineteen stations were observed. The results concluded that the artificial neural network requires sufficiently large number of inputs to accurately predict the target.

Kavitha and his co-author Felix Kala have proposed a study to investigate the seismic behavior of bamboo fibre reinforced self-compacting concrete exterior beam column joint. The authors studied the behavior of exterior bamboo fiber reinforced concrete beam-column joint with different modulus of elasticity. A three-storied RC building in the zone V is analyzed, and one of the exterior beam-column joints at an intermediate storey is designed in ETABS.15. The results showed that, this indicates failure accrue in bamboo fiber reinforced SCC beam-column joint and helps to compare the failure pattern with conventional SCC concrete replaced with GGBS and alccofine.

Garimella Raghu Chandra et al. have presented a study about the dynamic behavior of canal slope under blast load assessed using numerical modeling approach based on ground vibration samples. Studies were carried out at Yanakandla Mine, Kurnool District of Andhra Pradesh over a period of two months and blast vibrations were monitored at different distances. Based on the signal processing analysis made, regression based statistical analysis was carried out. Vertical joint was included in the model and analysis was carried out to determine the influence of joint in the rock mass. The results showed that, the dynamic behavior of canal slope under blast load based on ground vibrations were caused due to blasting operations.

Isha Patel and co-author Chandra Mohan Rao have analyzed the effect of geometric parameters on seismic performance of RC chimneys. The seismic behaviour of tapered chimneys of different heights with varying Height/ Bottom diameter ratio of the chimney (H/D ratios) and varying Bottom diameter/ Bottom Shell thickness ratio of the chimney (D/T ratios) has been investigated using SAP 2000 software. Free vibration analysis and seismic analysis were carried out in this study. The study concluded with the analysis and results about the effect of the geometric parameters of chimneys on dynamic response parameters.

EDITORIAL

Kavya Reddy and his co-author Chandra Mohan Rao have presented a study about the modal analysis of hyperboloidal shell structures. This paper deals with the modal analysis of hyperboloidal shell structures of two different heights (143.5 m and 175.5 m). Free vibration analysis has been carried out for all the designed models and analysis has been carried out using ANSYS. The study results concluded with the geometric parameter H/Dt ratios for various observations.

Jakkula Sowjanya and co-author Mallika Alapati have presented a study about the influence of patch location on damage detection of smart bar using EMI technique. For that, the effect of vibrations on the admittance signatures of the healthy and the corroded smart bar are studied for various patch locations. From the peak shifts of current output obtained for pristine and the corroded bar, it is found that change in EMI signatures serves as a sensitive diagnostic tool in the damage detection and also the patch location plays a significant role in the damage detection. The study results concluded that, not only the patch location from the damage, but also the distance from the constrained boundaries influence the sensitivity of the signatures.

I express heartfelt appreciation to all the authors and reviewers of i-manager Journal on Civil Engineering!

Enjoy Reading!

Warm regards,
Ramya R.
Associate Editor
i-manager Publications

NUMERICAL MODELLING BASED IMPACT OF GROUND VIBRATIONS

By

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ABSTRACT

The dynamic behavior of canal slope under blast load was assessed using numerical modelling approach based on ground vibration samples. Studies were carried out at Yanakandla Mine, Kurnool District of Andhra Pradesh over a period of two months and Blast vibrations were monitored at different distances. Based on the signal processing analysis made, regression based statistical analysis was carried out. In addition, curve fitting analysis made between Peak Particle Velocity of ground vibrations and Scaled Distance resulted in a very good coefficient of determination of about 92% between them. A Distinct Element Modelling technique in 3DEC software was carried out for finding the slope stability analysis of the canal located near the mine by adopting a simplified triangular blasting load. Vertical joint was included in the model and analysis was carried out to determine the influence of joint in the rock mass. It was observed that the Peak Particle Velocity values obtained from numerical modelling are in close approximation to the field investigation results.

Keywords: Numerical Modelling, 3DEC, Distinct Element Modelling, Triangular Blasting Load, Peak Particle Velocity.

INTRODUCTION

Slope stability analysis is becoming a major concern, as open cast mining contribute maximum to the total production in the mining industry. Hence, it is very crucial to evaluate the various potential failure mechanisms occurring in the slope and to take economically feasible steps to reduce, remove, and mitigate the risk associated with slope stability.

A mathematical model was also described to optimise the blast design for a specified damage zone in the rock mass. Seismic cross hole measurements were performed before and after the blast to monitor how the amplitudes and the transmission times changed after the blast and the results achieved from these holes showed that both the P-wave velocity and the maximum amplitude were reduced after the blast (Garimella, Chandra, & Parvathy, 2019; Sastry & Chandra, 2016a, 2016b).

Finally, the statistical curve fitting model was established by considering significant coefficients from statistical analysis. Values predicted by a model are verified by field investigation results to obtain satisfactory results. The developed models may be used for drawing graphs and analyzing results for forecasting purposes.

1. Literature Review

In order to tackle the problems related to stability, numerical modelling software are needed. Yang et al. (2012) have conducted a study of the dynamic behaviour of road high cutting rock slope under the influence of blasting for excavation. Numerical simulation by FLAC-3D (Fast Lagrangian Analysis of Continua in 3 Dimensions), a numerical modelling software was employed and the result showed that the particle vibration velocity simulated was consistent with that by field test (Chen, Cai, Zhao, & Zhou, 2000; Cheng et al., 2006; Deng, Zhu, Chen, & Zhao, 2012; Hassan & Damper, 2012; Israelsson, 1996; Lemos, 2004; Wang, Li, Zuo, Zhou, & Zhang, 2006; Zhang, Jing, Zhang, & Fan, 2008). Singh and Roy (2010) carried out a study on the effect of blast vibration on damage of surface structures and their study was focused on the determination of safe levels of ground vibration for residential structures and other buildings in the mining area. In an article by Xu and Yan (2006), a numerical simulation for the influence of excavation and blasting vibration on the stability of mined out area, dynamic analysis steps, and general flow of fast Lagrangian analysis of continua in FLAC 3D were discussed. Griffiths and Fenton (2004) had carried out a study on the topic of slope stability analysis by Finite Elements (FE) and described several examples of finite element stability analysis with comparison against other stability analysis methods. From the study, it was found that the FE method in conjunction with an elastic-perfectly plastic stress-strain method has been shown to be a reliable and robust method for assessing the factor of safety of slopes. Therefore, this method can be effectively used as an alternative to traditional limit equilibrium methods. Singh (2002) conducted a study on blast vibration damage to underground coal mines from adjacent open-pit blasting and investigated seven coal mines in India. Monitoring of strata behaviour was carried out before and after the blasts by installing the strata monitoring instruments in the roof and pillar and the threshold value of vibration for the safety of underground workings is recommended based on the Rock Mass Ratio (RMR) of the roof rock. Zeng and Xiao (2017) carried out a study on the topic of 'FLAC3D based Improvement for Strength Reduction Method's Slope Stability'. Further, they discussed the method for separate reduction of shear strength parameters such as friction angle and cohesion after obtaining the potential slide surface through the high value zone of horizontal displacement, and thus realized the dual safety coefficient method for slope stability evaluation. Cen and Jiang (2008) had carried out a study on blasting vibration control of creep mass high slope, that focuses particularly on hydropower station and control strategies over several damages due to blast vibration. Based on decay experience formula and damage standards due to blasting, the safety-controlled parameters of cast in situ concrete of the creep mass high slope were derived. Sastry, Rebello, and Shivashankar (2015) conducted a study on the topic of blast-induced response of a tunnel in the presence of a two-storied structure. In this study, they have taken three velocity-time histories of different PPV (Peak Particle Velocity) and applied at three different boundaries of the model. In addition, they studied the effect of varying input PPV's and their frequencies on the stability of building and tunnel. Results of the study indicated that peak velocity response occurs in the beams of the top floor and greater displacement occurred at the top of the building and also concluded that irrespective of location of application of input waves, maximum concentration of stress occurred at the tunnel sides. Kahriman (2004) conducted a study on the analysis of ground vibration parameters produced from bench blasting at a limestone quarry, to predict peak particle velocity level at a limestone quarry located in Istanbul, Turkey. Further, an empirical relationship with good correlation was established between peak particle velocity and scale distance for this site. Holmberg and Maki (1981) had done a study on case examples of blasting damage and its influence on slope stability. They introduced simulated blast damage into samples before testing the shear strength to show the blasting damage influence on the slope stability.

2. Investigations and Details

2.1 Field Investigations

General location and accessibility map of the lease area are shown in Figure 1.

2.2 Area of Study

Blast vibration studies were carried out in Yanakandla Mine at Yanakandla Village in Banaganapalli Mandal, Kurnool District of Andhra Pradesh. The problem of concern in the present case was the ground vibration of nearby Canal. The excavated irrigation Galeru Nagari Sujala Sravanthi (GNSS) canal is traversed along deposit periphery towards the north-west side of mine. It is proposed by the mine management to advance the benches to 50 m towards the canal side, simultaneously maintaining the safety of the canal. Statistics of Yanakandla limestone mine as on 31.03.2015 is shown in Figure 2. Figure 3 shows the GNSS canal located near the mine lease area.

To assess the impact of blasting operations, eight

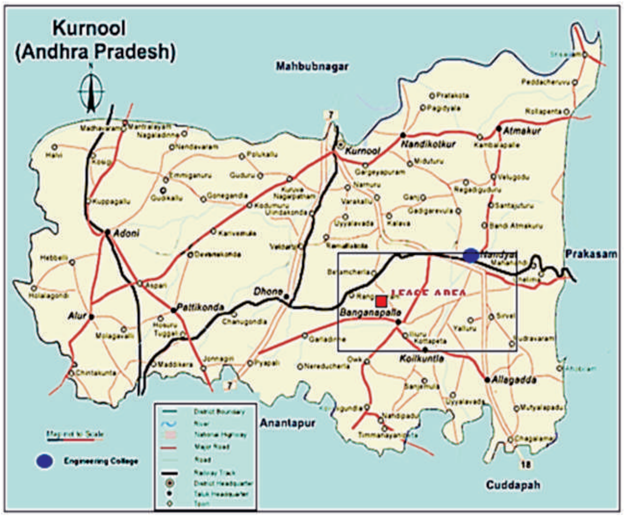

Figure 1. General Location and Accessibility Map of the Lease Area

Figure 2. Statistics of Yanakandla Limestone Mine as on 31.03.2015

production scale blasts conducted at different locations in Yanakandla Limestone Mine were studied. Blastholes of 115 mm diameter were drilled using wagon drills. Depth of blastholes varied from 6 to 7 m in different blast rounds. Each blasthole was charged with ANFO mixed with husk as column charge. Slurry explosive was used as Primer charge, with cartridges of 2.78 kg each, making the explosive charge per hole to 14.35 to 39.06 kg. Exel Dueldet shock tube system of initiation was used, simultaneously providing the in-hole initiation and surface delay. The pattern of explosive column and stemming in

Figure 3. GNSS Canal Located Near the Mine Lease Area

blasthole was changed from blast to blast. Figure 4 shows the general view of the mine.

Locations of different blasts studied in the Yanakandla limestone mine are shown in Figure 5. Layouts of all the blasts studied are given in the figure. All the eight production blast vibrations were recorded using minimates. B-1, 2, 3, 4, 5, 6, 7, 8 indicates respective blast locations.

2.3 Monitoring Vibrations

Blast vibrations are monitored using the instrument Instantel Minimate Plus. The vibrations were captured by means of geophones kept at different distances, i.e. 30, 40, 50, 60, 70, 80, 90, and 100 m. Ground vibrations captured by the

Figure 4. Locations of Blast Rounds Studied

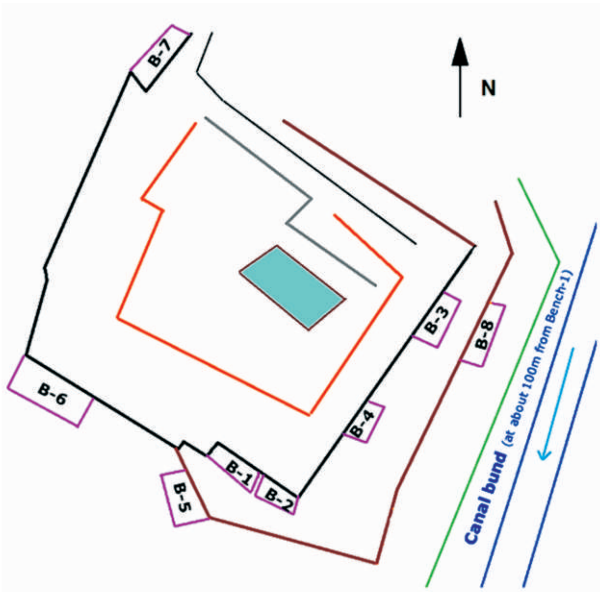

Figure 5. General View of the Mine

sensors in geophones were downloaded into a computer using external accessories and these data were analysed using Blastware software. Hence the peak particle velocity, frequency, and acceleration of each vibration was obtained from the software along with the FFT report of each event. Monitoring of ground vibration using geophone is as shown in Figure 6.

2.4 Regression Analysis

The intensity of ground vibrations recorded at different distances was obtained from Blastware software. Based on this data, a regression curve was plotted with peak particle velocity v/s scaled distance as shown in Figure 7. From the data generated, the ground vibration propagation equation for Yanakandla limestone mining project site has

Figure 6. Monitoring of Ground Vibration

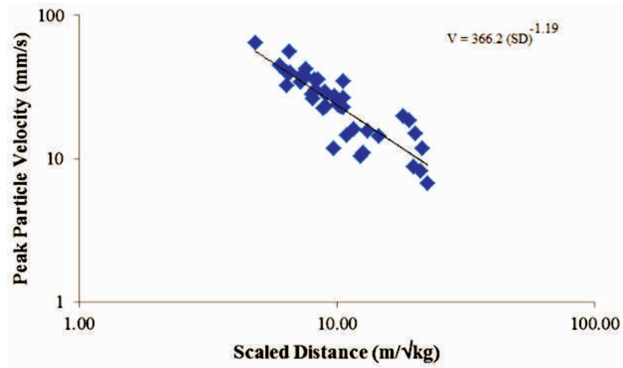

Figure 7. Peak Particle Velocity vs. Scaled Distance

been established as,

$$V = 366.2\,(SD)^{-1.19}$$

where,

SD = D/ÖW

V = Peak particle velocity (mm/s)

D = Distance between blast site and location of instrument / structure (m)

W = Maximum explosive charge / Delay (kg)

Using the established ground vibrations propagation equation, the expected Peak Particle Velocity values are estimated for different distances, with different explosive charges/delay. The values are tabulated and shown in Table 1.

With 25 kg of MCD, the PPVs expected are about 43 mm/s at 30 m distance, 31 mm/s at 40 m distance and 24 mm/s at 50 m distance. With 35 kg of charge / delay, a PPV of about 53.05 mm/s is expected at 30 m distance, 37.67 mm/s at 40 m distance, 28.88 mm/s at 50 m distance, and 12.66 mm/s at 100 m distance. Similarly, PPVs expected from a MCD of 30 kg are 48.4 mm/s at 30 m, 34.37 mm/s at 40 m, 26.35 mm/s at 50 m, 11.55 mm/s at 100 m distance, etc.

Distance (m)	Expected PPV (mm/s) levels for *MCD's of						
	10 kg	15 kg	20 kg	25 kg	30 kg	35 kg	40 kg
30	25.2	32.0	38.0	43.4	48.4	53.1	57.4
40	17.9	22.8	27.0	30.8	34.4	37.7	40.8
50	13.7	17.5	20.7	23.6	26.4	28.9	31.3
100	6.0	7.7	9.1	10.4	11.6	12.7	13.7
150	3.7	4.7	5.6	6.4	7.1	7.8	8.5
200	2.6	3.4	4.0	4.5	5.5	5.6	6.0
250	2.0	2.6	3.1	3.5	3.9	4.3	4.6

*MCD: Maximum Explosive Charge / Delay (kg)

Table 1. Expected PPV Levels at Different Distances for Different Maximum Charge/Delay

2.5 Physical Mechanical Parameters of Rock Mass

The physical, mechanical parameters of rock mass required for numerical modelling were obtained through laboratory tests. The rock properties of the considered strata are listed in Table 2.

3. Numerical Modelling

3.1 Dynamic Analysis by 3DEC

In order to study the process and mechanism of dynamic instability of the slope under blast vibration load, three-dimensional numerical simulations were carried out. Simulation study of canal slope stability was carried out using Three Dimensional Distinct Code (3DEC-Version 3.1) developed by Itasca Consulting Group Inc. In order to set up a model to run a simulation with 3DEC, the fundamental components of a problem to be specified include a distinct element model that matches the problem geometry, constitutive behaviour and material properties, boundary and initial conditions, static and subsequent dynamic analysis. For analysis, blast load is applied and peak particle velocity was simulated at a distance of 30, 40, 50, 60 m by numerical modelling. PPV, displacement, and stress was analysed in each case. In addition, analysis was done considering a vertical joint extending to 5 m and 10 m below the canal bottom at a distance 30 m away from the canal edge. A 3DEC model of canal slope after excavation is shown in Figure 8.

3.2 Velocity Time History Curve as Blasting Vibration Input

Vibration velocity was chosen as the physical parameter for field test using blast vibration transducers. Figure 9 shows the velocity series of blast vibration recorded from the blast site under consideration with the dominant frequency of 21.5 Hz, Blasting time of 1s, and the maximum amplitude of 0.508 mm/s. The velocity time history of the wave used as blasting vibration input is shown in Figure 9.

3.3 Application of Dynamic Load

In order to find out the law of redistribution of secondary state of stress and variance of velocity and displacement

Rock Type	Density (kg/m^3)	Bulk Modulus (Pa)	Rigidity Modulus (Pa)	Cohesion (KPa)	Angle of Internal Friction
Limestone	2500	16 x 10^9	6.7 x 10^9	2000	400

Table 2. Rock Properties of the considered Strata

Figure 8. 3DEC Model of Canal Slope after Excavation

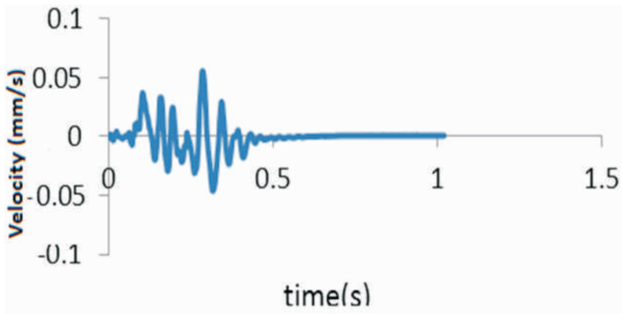

Figure 9. Velocity Time History of Wave

under blast vibration, the whole analysis is divided into two steps, which are static and dynamic analysis. In 3DEC, acceleration, velocity, displacement, and stress are the dynamic mode of input for the dynamic computation and analysis. For viscid boundary condition, dynamic loads input must be velocity.

4. Results and Discussions

The distribution of maximum principle stress due to dynamic loads are shown in Figure 10. The displacement contours and velocity contours of the model under blast loads are shown in Figures 11 and 12, respectively. For further analysis, some points say A, B, C, D, E, F, G, H are considered along the canal slope and also below the bottom of the canal as shown in Figure 13.

The velocity time history and displacement time history generated under frequency 21.5 Hz is shown in Figures 14 and 15, respectively. As a parametric study, a vertical joint of width 1mm with loose cohesive clay was also analysed. A vertical joint extended to 5 m and 10 m below the canal bottom was analysed to determine the effect of joints in the rock mass. The displacement contours and velocity contours in the presence of vertical joint is displayed in Figures 16 and 17, respectively.

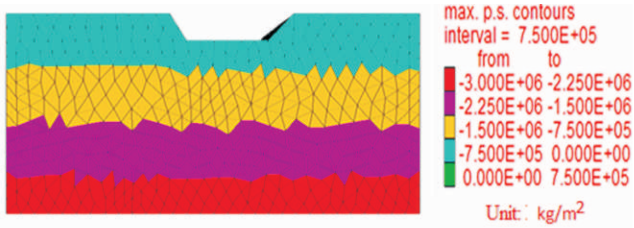

Figure 10. Distribution of Stress under Dynamic Loading

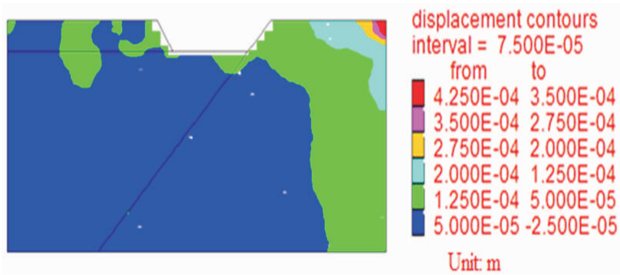

Figure 11. Distribution of Displacement under Dynamic Loading

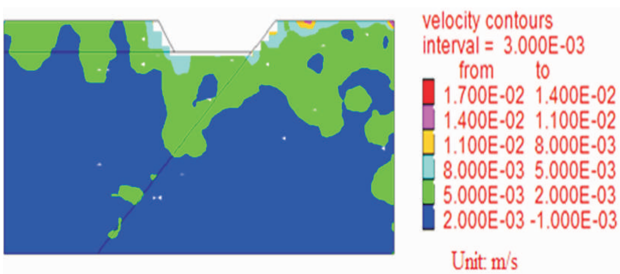

Figure 12. Distribution of Velocity under Dynamic Loading

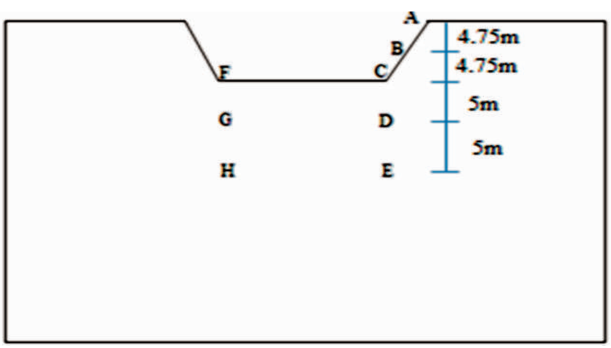

Figure 13. Points considered for Analysis

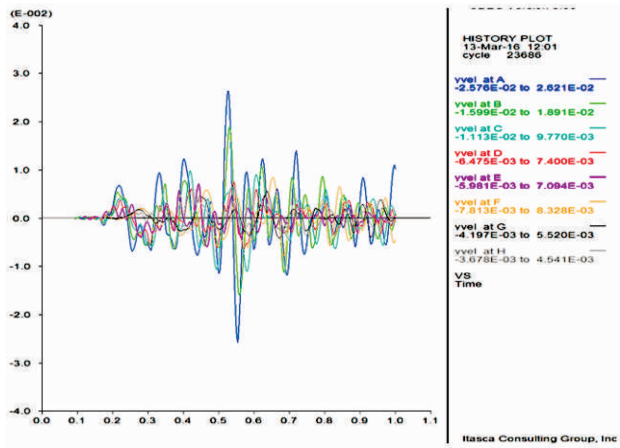

Figure 14. Velocity Time History Generated in 3DEC under Frequency 21.5 Hz

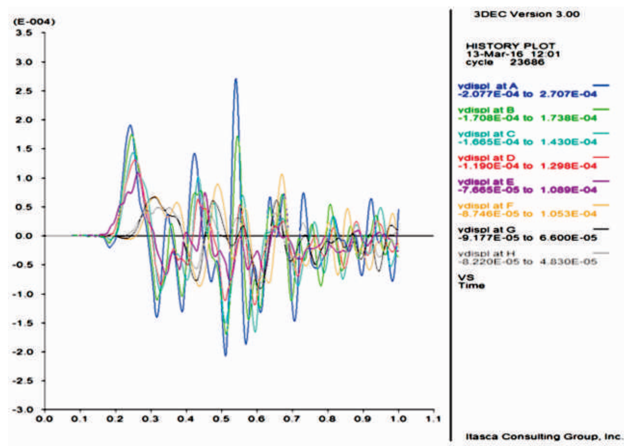

Figure 15. Displacement Time History Generated in 3 DEC under Frequency 21.5 Hz

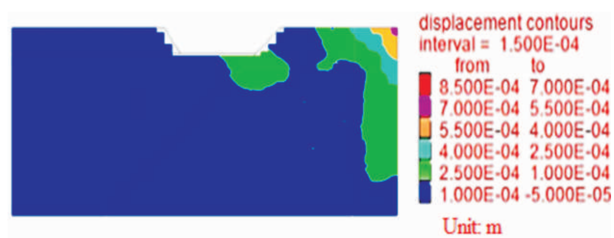

Figure 16. Distribution of Displacement under Dynamic Loading in the Presence of Vertical Joint

Analysis of velocities and displacements at different distance and different points with and without vertical joints was done. Vertical velocity and vertical displacements at different distances for considering points was tabulated in Tables 3 and 4, respectively. From the results obtained, it can be observed that as the distance where the impact of dynamic load is considered increases, the PPV and displacement decreases. The influence of a vertical joint in rock mass on vertical velocities and vertical displacements was shown in Table 5.

Conclusions

In the present research study, detailed field investigations were carried out to estimate the dynamic behaviour of canal slope under blast load based on ground vibrations caused due to blasting operations. Studies were carried out over a period of two months at different locations of Yanakandla Mine, Kurnool District of Andhra Pradesh.

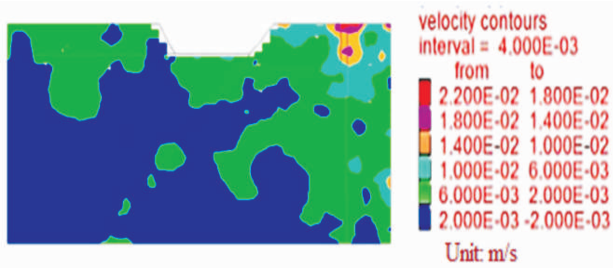

Figure 17. Distribution of Velocity under Dynamic Loading in the Presence of Vertical Joint

Points Considered	Vertical Velocity (mm/s), when Blast is Simulated at a Distance 'X' from the Slope of the Canal			
	X = 30 m	X = 40 m	X = 50 m	X = 60 m
A	35	33.12	26.21	25.1
B	29	18.9	18.91	17.93
C	23	22.38	11.11	18.18
D	17	9.87	7.4	8.24
E	14	9.05	7.09	11.24
F	21	9.86	8.33	19.15
G	14	7.5	5.52	13.41
H	9.7	6.07	4.54	6.22

Table 3. Vertical Velocity at Different Points Considered

Points Considered	Vertical Displacement (mm), when Blast is Simulated at a Distance 'X' from the Slope of the Canal			
	X = 30 m	X = 40 m	X = 50 m	X = 60 m
A	0.41	0.373	0.271	0.264
B	0.32	0.266	0.174	0.226
C	0.31	0.276	0.166	0.206
D	0.24	0.196	0.129	0.136
E	0.21	0.165	0.109	0.123
F	0.27	0.151	0.105	0.205
G	0.23	0.115	0.092	0.145
H	0.71	0.112	0.082	0.1

Table 4. Vertical Displacement at Different Points Considered

Points Considered	Vertical Velocity (mm/s) with a Joint Height up to 'Z' m below Canal Bottom		Vertical Displacement (mm) with a Joint Height up to 'Z' m below Canal Bottom	
	Z = 5 m	Z = 10 m	Z = 5 m	Z = 10 m
A	22.92	14.34	0.266	0.202
B	20.75	18.25	0.235	0.239
C	15.16	13.15	0.185	0.232
D	8.04	6.45	0.167	0.186
E	7.51	9.79	0.156	0.149
F	10.83	9.87	0.157	0.13
G	9.55	6.74	0.59	0.127
H	4.79	5.23	0.114	0.124

Table 5. Vertical Velocity and Vertical Displacement with Vertical Joint at Different Points

Following are the main conclusions drawn from the research study,

- The PPV values obtained from regression analysis using field vibration monitoring data are in the par with the results from numerical modelling.
- It was clear from the modelling results that the presence of a vertical joint reduces the PPV and the displacement values. In addition, with the increase in the height of the vertical joint, the values of the PPV and displacement were again reduced.
- From the modelling results and field data, with the increase in length of blast load from the point of observation, PPV and displacement values decreased.
- From the simulation results, it was clear that velocity and displacement will be maximum at surface and it reduces as it goes deeper.

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Case 1a. Healthy Steel Bar with Patch Location at 10 mm

Case 2a. Healthy Steel Bar with Patch Location at 50 mm

Case 1b. Bar with 2 mm Corrosion Depth with Patch Location a 10 mm

Case 2b. Bar with 2 mm Corrosion Depth with Patch Location at 50 mm

Case 1c. Bar with 4 mm Corrosion Depth with Patch Location a 10 mm

Case 2c. Bar with 4 mm Corrosion Depth with Patch Location at 50 mm

Case 3a. Healthy Steel Bar with Patch Location at 90 mm

Case 3b. Bar with 2 mm Corrosion Depth with Patch Location at 90 mm

Case 3c. Bar with 4 mm Corrosion Depth with Patch Location at 90 mm

Figure 1. Geometry of Smart Bar for Various Cases

Length (mm)	Depth (mm)	Breadth (mm)	Young's Modulus (Pa)	Poisson's Ratio	Density (kg/m^3)	Damping Ratio
300	8	10	2×10^{11}	0.3	7850	0.0015

Table 2. Properties of the Beam

Length (mm)	Depth (mm)	Breadth (mm)	Density (kg/m^3)	Damping Ratio
10	0.3	10	7800	0.005

Table 3. Geometric Properties of the PZT Patch

ANSYS. Harmonic analysis with stepped frequency is performed and the output current flow is recorded.

3. Results and Discussion

3.1 Modal Analysis

Modal analysis is performed on the steel bar for the three cases. The changes occurred in the fundamental natural frequencies are compared to the healthy steel bar and the corroded bars. Natural frequency changes for various corrosion depths for the cases considered are represented in Table 5 and Figure 2.

Anisotropic Properties (N/m^2)		Relative Permeability (F/m)		Piezoelectric Matrix (C/m^2)	
D11	1.5×10^{-11}	PERX	1977.4	K13	-2.1×10^{-10}
D12	4.5×10^{-12}	PERY	1977.4	K23	-2.1×10^{-10}
D13	5.7×10^{-12}	PERZ	2395.5	K33	5×10^{-10}
D22	1.5×10^{-11}	-	-	K42	5.8×10^{-10}
D23	-5.7×10^{-12}	-	-	K51	5.8×10^{-10}
D33	1.9×10^{-11}	-	-	-	-
D44	3.9×10^{-11}	-	-	-	-
D55	3.9×10^{-11}	-	-	-	-
D66	4.94×10^{-11}	-	-	-	-

Table 4. Material Properties of the PZT Patch

From Table 5, it is observed that the natural frequencies have decreased as the corrosion depth increased. This is due to the change in the volume in turn in mass. Natural frequency is indirectly proportional to the square root of the mass, a decreasing trend is observed as the corrosion depth increased.

As the volume changes are constant in all the three cases for the three patch locations subsequently, the natural frequencies remain the same in each sub case (healthy bar, bar with 2 mm corrosion depth and bar with 4 mm corrosion depth).

3.2 Harmonic Analysis

Harmonic analysis is used to find the steady state response of the bar subjected to sinusoidal loads. An alternating voltage of 1V is applied to the PZT on both top and bottom surface of the patch. The reaction output of current is captured and plotted as shown in Figures 3, 4, and 5,

Case	Mode No	Healthy Bar	2 mm Corrosion Depth	4 mm Corrosion Depth
Case 1	1	72.707	66.238	49.043
	2	90.709	89.955	86.635
	3	453.85	386.4	322.56
	4	565.45	564.79	562.37
	5	1263.6	1125.9	860.01
Case 2	1	72.653	66.202	49.031
	2	90.687	89.936	86.62
	3	453.16	385.77	322.03
	4	565.11	564.42	561.98
	5	1261.8	1124.1	858.36
Case 3	1	72.608	66.165	49.016
	2	90.666	89.913	86.599
	3	453.02	385.43	321.64
	4	564.82	564.02	561.44
	5	1262.1	1123.6	857.07

Table 5. Natural Frequencies of Modal Analysis