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Dynamic numerical analysis of the effect of tunneling-induced vibration on combined heat and power plant structures under operation

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Abstract. The power plant is a major infrastructure composed of essential machinery such as Turbine Generators (TG), Heat Recovery Steam Generators (HRSG), etc. Particularly, Combined Heat & Power Plants (CHP) are highly efficient power plants that simultaneously produce heat and electricity. Recently, cases have emerged where railway tunnels are being constructed beneath such power plants due to the underground development of urban rail transportation. Therefore, there is a pressing need to assess the impact of vibrations induced by blasting excavation during the construction of railway tunnels beneath the power plant, as well as the vibrations during railway operation, on the major machinery foundations and structures within the power plant. In this study, criteria for evaluating the vibration impact on key vibration-sensitive structures are summarized, and evaluation standards based on international criteria are established. Based on this, the study examines the vibration impact during the blasting excavation method of NATM tunnels beneath the operational power plant. Furthermore, subsequent railway operation, specifically focusing on the impact of train vibrations on Turbine foundations, Pump foundations, and District Heating pipelines using 3D dynamic numerical analysis. The results indicate that vibration values corresponding to up to 97.3% of the evaluation criteria are derived based on the numerical analysis. However, considering the significance of power plant-related structures, additional measures to reduce vibrations are proposed, including further test blasting, alteration of blasting patterns, reducing the charge per delay, or decreasing advance.

Keywords: 3D dynamic numerical analysis; blasting excavation; district Heating pipelines; power plant; railway tunnels

1. Introduction

Power plant is highly critical industrial facility that integrate primary equipment such as Gas Turbine Generator (GTG), Steam Turbine Generator (STG), Heat Recovery Steam Generators (HRSG), and various auxiliary facilities, interconnected structures, and piping networks, i.e., district heating pipelines, to produce electricity or both electricity and heat. In particular, combined heat and power plant (CHP) primarily operates turbine generators to produce electricity and utilize the turbine's exhaust gas to generate thermal energy, resulting in higher efficiency compared to conventional thermal power plant and the potential reduction of environmental pollution (Choi *et al.* 2017). In the event of incidents occurring in such combined heat and power plant, the societal and economic ramifications are significant, encompassing damages to various machinery and structures within the power plant, substantial financial losses due to interruptions in electricity and heat production, and personnel injuries among the workforces. Therefore, particular attention must be paid to ensuring safety during design and construction activities near the operational power plants. With recent urban expansion and increased development projects such as the construction of new transportation networks like Great Train Express (GTX), as a metropolitan express railway system, there is a surge in tunnel construction. Instances of passing through or closely approaching the substructures of existing plant facilities are becoming more frequent in such scenarios (Guan *et al.* 2023).

Especially in the case of tunnel construction in South Korea, the prevalent characteristics of sturdy bedrock and relatively lower construction costs have led to the widespread application of the New Austrian Tunnelling Method (NATM) using blasting excavation. Therefore, during tunnel excavation, it is essential to assess not only the static stability of power plant facilities but also the dynamic response resulting from blasting. Ozacar (2018) proposed a method for determining the most suitable time delays to avoid overlapping vibrations by analyzing peak particle velocity and dominant frequencies through vibration measurements during tunnel blasting in 1-2 story masonry or concrete houses adjacent to the tunnel. Ihsan *et al.* (2023) optimized the estimation method on ground vibrations during blasting excavation in a limestone quarry using artificial neural networks and compared it with a

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conventional blast vibration predictor model. The results confirmed that the distance from the blast source accounts for 83% of the impact on ground vibrations, with factors such as blast hole depth and the number of blast holes during blasting contributing to the remaining 17%. This validates the importance of the distance from the blast source in ensuring safety. Lee *et al.* (2022) performed a comparative analysis of various center-cut methods, specifically the commonly applied V-cut method and the recently prevalent double-drilled parallel method, for vibration reduction during tunnel blasting. The study utilized both blasting experiments and 3D finite difference analysis. The results indicated a decrease in peak particle velocity with the application of the double-drilled parallel method.

Furthermore, after the tunnel construction, the vibration loads induced by train operations within the tunnel can impact the operation of extremely sensitive vibrating machinery such as turbines. Hadi *et al*. (2023) conducted a three-dimensional numerical analysis to examine the dynamic interference effects of high-speed trains running on ballasted railway track system on the settlement of the track. The analysis revealed that during adjacent moving of the high-speed train, the train speed and the distance between the moving train have a significant effect on track settlement, with the influence of ballasted track thickness and stiffness being relatively minor. Farghaly and Kontoni (2018) performed a long-term observation of the influence of water content in the ground when constructing a pedestrian tunnel beneath a 4-track surface railway in operation. They analyzed the impact of water content variations near the tunnel and ground subjected to train-induced vibrations using 3D finite element analysis. However, they confirmed that these variations in water content did not significantly affect the overall structural stability of the tunnel. He and Zhou (2023) conducted an analytical review of the dynamic interaction in the track-tunnel-ground system, considering the induced ground vibrations during the operation of double-line trains in underground tunnels. The results indicated that ground vibrations during the simultaneous passage of trains increased by more than 30%.

In previous studies, various analytical methods (FEM, FDM) and on-site measurements have been employed. However, cases examining the influence of blast-induced vibrations near an operational combined heat and power plant are very limited, with most studies focusing on residential areas or existing structures. In this study, the characteristics and effects of vibrations induced by both blasting during the excavation of a railway tunnel beneath an operational combined heat and power plant and the passage of trains within the tunnel were separately evaluated. A Korean domestic site is employed for this study. To assess the impact of blast-induced vibrations, criteria for blast vibration tolerance were established. Dynamic numerical analysis using 3-dimensional finite element analysis was performed on critical vibration-sensitive foundations within the plant, such as turbine foundations and pump foundations. For the evaluation of vibration effects induced by train operations, train vibration loads were calculated and applied to the analysis. Additionally, to validate existing ground investigation results, additional borehole investigations were conducted at the location closest to the tunnel, and the findings were incorporated in determining the ground properties. Furthermore, to overcome the limitations of numerical analysis, a detailed monitoring plan applicable during future construction was proposed.

Table 1 The criteria for regulating the use of explosives

Area	Day (06:00～22:00)	Night (22:00～06:00)
- Residential & Green belt area - Management area - Natural environment conservation zone - Tourism promotion zone - School, general hospital, public library	≤ 65 dB(V)	≤ 60 dB(V)
Others	≤ 70 dB(V)	≤ 65 dB(V)

2. Vibration design criteria

The railway tunnel passing beneath the plant is designed using the NATM method, requiring repetitive blasting operations. Therefore, as blasting-induced vibrations affect adjacent structures and the ground, it is crucial to establish and manage reasonable design criteria for the safety against vibrations. In accordance with Korean domestic regulations related to the construction vibration, Article 25 of the Noise and Vibration Management Act stipulates the prevention of noise and vibrations caused using explosives. It specifies that local government heads can request the police chief of the city or province to take regulatory measures on the use of explosives. The criteria for regulating the use of explosives are outlined in Article 20, Paragraph 3, Attachment 8 of the Enforcement Regulations of the Noise and Vibration Management Act, which can be summarized in Table 1 as follows.

As indicated in Table 1, the Noise and Vibration Management Act is the sole regulation in Korea that addresses blasting air overpressure and ground vibration. However, this regulation primarily focuses on residential noise and vibration, utilizing vibration level (dB(V)) as the measuring unit. It is impractical to engineer the assessment of blast vibrations caused by temporary impact loads using vibration levels as they pertain to the effects of blast vibrations (Choi and Ryu 2012).

Therefore, to supplement this, safety criteria for vibration assessments during blasting operations are typically established by considering the impact of ground vibrations on structural damage. The peak particle velocity (PPV) is chosen as the safety criterion in such vibration evaluations. The unit for PPV is kine (cm/s), and it is deemed valid to calculate it as the vector sum of vibration components along three orthogonal axes.

Table 2 Case review for blasting-induced vibration (Modified after Kwak *et al.* 2023)

Case	Condition	Allowable criteria
Extension PJT for ○○ Combined heat and power plant (1994.10)	39 m of Min. distance	0.25 g
	42 m of Min. distance	0.25 g
Crossing tunnel under Namhansanseong Fortress (1994.12)	30 m / 20 m of Min. distance	0.2 kine
Nashin deptment store (1995.01)	5.8 m / 13 m of Min. distance	0.5 kine
○○ Combined heat and power plant (2012.08)	40 m of Min. distance to Turbine	0.2 kine

Table 3 Case review for previous vibration guideline (Modified after Kwak *et al.* 2023)

Guideline	Allowable vibration criteria	Remarks
Design Standard of Railway (2011)	0.2 ~ 0.3 kine	Cultural assets and vibration-susceptible equipment
Specialized specifications for expressway (Korea Expressway Corporation, 2006)	0.1 kine	Livestock
	0.2 kine	Cultural assets and vibration-susceptible equipment
Specifications for subway construction in Seoul	0.2 kine	Cultural assets and buildings including precision devices
Technical specifications for nuclear power plant	0.2 kine	Under operation of precision devices
	2.54 kine	etc.
○○ petrochemical factory	0.2 kine	Substation

In this study, cases of vibration-sensitive structures or blasting near power plants were reviewed, as presented in Table 2. The results confirmed the application of criteria ranging from 0.2 to 1.0 kine

Additionally, the results of a review of major domestic institutions and similar construction cases are presented in Table 3.

Upon examining the existing cases and practical application criteria, it was found that, excluding livestock, a practical and stringent criterion of 0.2 kine is predominantly applied. International guidelines, provided by the International Organization for Standardization (ISO), establish criteria for high-speed rotating machinery. These guidelines can be applied based on the capacity ratings of turbines and pumps that undergo high-speed rotational motion within the plant (see Table 4). The capacity ratings for the rotating vibrating machinery, which is the primary focus of this study, are calculated and presented in Table 5.

Table 4 ISO 10816-1 guidelines for rotating vibrating machinery

<table>
<tr><th rowspan="3">Velocity severity</th><th colspan="4">Velocity range limits and machine classes</th></tr>
<tr><th rowspan="2">Small machines</th><th rowspan="2">Medium machines</th><th colspan="2">Large machines</th></tr>
<tr><th>Rigid supports</th><th>Less rigid supports</th></tr>
<tr><td>kine (peak)</td><td>(Class I)</td><td>(Class II)</td><td>(Class III)</td><td>(Class IV)</td></tr>
<tr><td>0.05</td><td rowspan="3">Good</td><td rowspan="4">Good</td><td rowspan="5">Good</td><td rowspan="6">Good</td></tr>
<tr><td>0.07</td></tr>
<tr><td>0.10</td></tr>
<tr><td>0.15</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>0.25</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>0.40</td><td rowspan="2">Unsatisfactory (Alert)</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>0.63</td><td rowspan="2">Unsatisfactory (Alert)</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>1.01</td><td rowspan="4">Unacceptable (Danger)</td><td rowspan="2">Unsatisfactory (Alert)</td></tr>
<tr><td>1.57</td><td rowspan="3">Unacceptable (Danger)</td><td rowspan="2">Unsatisfactory (Alert)</td></tr>
<tr><td>2.54</td><td rowspan="2">Unacceptable (Danger)</td></tr>
<tr><td>3.96</td><td rowspan="2">Unacceptable (Danger)</td></tr>
<tr><td>6.37</td><td></td><td></td><td></td></tr>
</table>

Table 5 Capacity ratings of turbine and pump

Machines	Capacity	Rating
Steam turbine	68.7MWe (@ 15℃) (92,128 HP)	Class IV
Gas turbine	86.8MWe (@ 15℃) (116,401 HP)	Class IV
DH SUPPLY PUMP 121-M-PP-001/002/003 (Model : 600×500)	670 kW (898 HP)	Class III
DH RESERVE PUMP 121-M-PP-004 (Model : 600×500)	1,200 kW (1,609 HP)	Class III
DH RETURN PUMP(PLB#2) 121-M-PP-005 (Model : 400×350)	360 kW (483 HP)	Class II
DH RETURN PUMP(PLB#1) 121-M-PP-006 (Model : 500×400)	500 kW (671 HP)	Class III
DH RETURN PUMP(CHP) 121-M-PP-007 (Model : 600×500)	800 kW (1,073 HP)	Class III
ACCUMULATOR PUMP 121-M-PP-008/009 (Model : 400×350 DSN)	400 kW (536 HP)	Class III

Vibration tolerance criteria specified by the equipment manufacturer are also outlined in Table 6.

In this study, the vibration criteria for blast-induced vibrations were determined by comprehensively

Table 6 Vibration tolerance criteria by manufacturer

Machines	Manufacturer	Criteria
Gas turbine	MES	Alarm : 2.54 mm/sec (0.254 kine) Alarm : 0.15 mm
Steam turbine	GE	Alarm : 0.125 mm
Pump	DH Reserve PP.	Limitation : 0.7 kine
	DH Supply PP.	Limitation : 0.7 kine
	DH PLB PP.	Limitation : 0.7 kine
	DH CHP PP.	Limitation 0.7 kine
	DH ACC PP.	Limitation : 0.7 kine

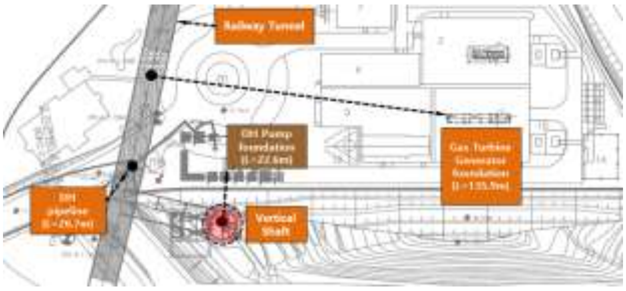


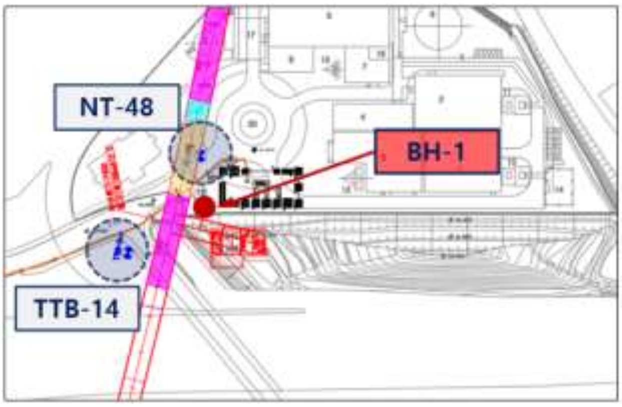
Fig. 1 Locations of target structures

considering the significance of equipment within the plant and the sensitivity of high-speed rotating machinery such as turbines. The capacity ratings of rotating vibrating machinery are categorized into Grades I to IV based on the machine's output and specifications. Consequently, after a comprehensive review as presented in Table 5, the most conservative criterion from Table 4, which is 0.15 kine (Grade II), was selected. This decision was made by considering the sensitivity of high-speed rotating machinery such as turbines and their importance within the plant. Apart from the rotating machinery, the design vibration criteria of district heating pipeline (DH pipeline) are suggested to be 0.4 kine based on the Korea District Heating Corporation (KDHC). All those criteria are regarded as the standard guideline to determine the dynamic stability of the concerning structures.

3. Numerical analysis conditions

The numerical analysis in this study focused on critical vibrating foundations within the plant, specifically the turbine foundation, and DH pipeline (with 26.7 m from the blasting source) and the pump foundation (with 22.6 m from the blasting source) in consideration of their distances from the source. The locations of the target structures including vertical shaft and railway tunnel are depicted in Fig. 1.

Given the current situation where tunnel construction has not commenced, the most practical method to understand the behavior of the ground and adjacent structures under blast-induced vibration is seems to be



(a) Location of boreholes

(b) Additional borehole drilling

Fig. 2 Additional borehole investigation

numerical analysis. Therefore, in this study, dynamic numerical analysis was conducted using the finite element analysis method, specifically employing the time-history analysis based on ABAQUS, a general-purpose code. This approach allows for a realistic assessment of the ground and adjacent structural response during blast loading conditions before the tunnel construction begins.

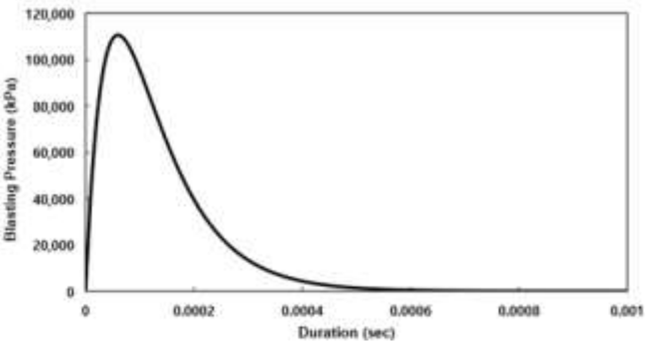
3.1 Geotechnical properties

Geotechnical properties for numerical analysis were determined based on the results of previous geotechnical investigations. To validate the adequacy of these results, additional borehole (BH-1) was drilled, and the findings were compared and reviewed. During the supplementary borehole investigation, the initial 2.5 m was excavated through test pit to confirm interference with subsurface structures and the final depth was 46.0 m. The locations of the existing boreholes (NT-48, TTB-14) and the additional borehole, along with the view before drilling, are illustrated in Fig. 2.

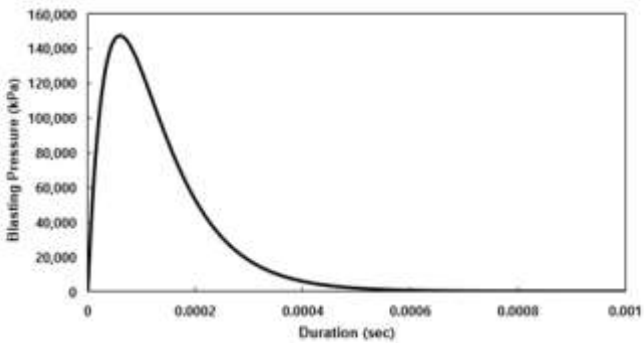
Based on the previous and additional soil investigation results, geotechnical properties are determined as shown in Table 7.

Table 7 Geotechnical properties

Type		Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Coeff. of deformation (MPa)	Coeff. of dynamic deformation (MPa)
Landfill	Clay	17.5	30.0	0.0	4	146
	Sand	18.0	5.0	27.0	10	205
	Gravel	18.5	0.0	30.0	27	353
Sedimentary layer	Clay (N≤6)	17.0	23.0	0.0	1	125
	Clay (N>6)	18.0	37.0	0.0	7	152
	Sand	18.0	3.0	28.0	10	275
	Gravel	18.5	0.0	33.0	40	523
Weathered soil	N≤30	18.0	20.0	29.0	45	423
	N>30	19.0	24.0	30.0	70	788
Weathered rock		21.0	32.0	32.0	210	1,829
Soft rock		23.0	400	34.0	2,000	4,600
Hard rock		26.0	2,500	42.0	12,000	12,918



(a) railway tunnel



(b) vertical shaft tunnel

Fig. 3 Blast load time histories

Blast load was determined by performing four test blasts in the borehole (Test Blast 1) and inducing the blast vibration estimation equation. Considering factors such as the maximum charge per delay and safety distance, etc., the blast load was calculated as shown in Fig. 3. There are 2 blast load time histories since the sources are different. The one is from the railway tunnel, and the other is from the vertical shaft tunnel, as depicted in Fig. 1. This blast load time histories are based on the exponential function form

Table 8 Parameters for blast load estimation

Items	Properties	Unit	Values
Explosive (emulsion)	Diameter	mm	32
	Specific gravity	g/cm^3	1.2
	Detonation velocity	m/sec	5,700
	Input detonation velocity	ft/sec	18,701
Tamping (sand)	Unit weight	g/cm^3	1.8
	Elastic wave velocity	ft/sec	600
Etc.	B	-	16,338
	Weight per delay	kg	15
	Borehole diameter	mm	45
	Borehole circumference	mm	141

Table 9 Specifications of target structures

Structure	Type	Specification
Gas Turbine Generator foundation	Shallow foundation	RC, f_{ck} = 24 MPa
PUMP foundation	Shallow foundation	RC, f_{ck} = 24 MPa
DH pipeline	Pre-insulated Pipe	600A, Soil depth = 1.6 m Outer diameter = 607.6 mm Thickness = 8.5 mm Insulated diameter = 800 mm

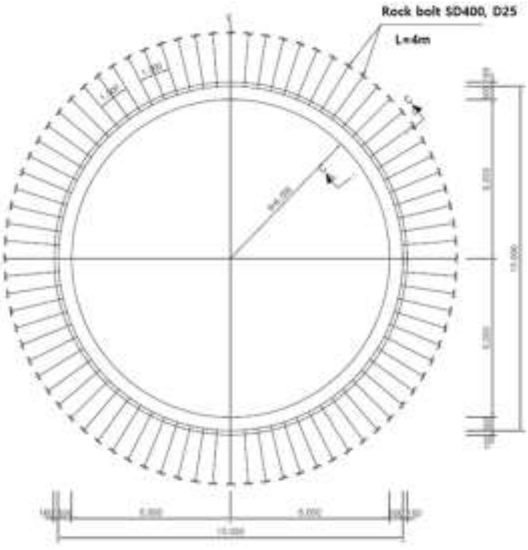
which is suggested by Starfield and Pugliese (1968) as shown below, and parameters are displayed in Table 8.

$$P(t) = 4P\left(\exp\left(\frac{-Bt}{\sqrt{2}}\right) - \exp(\sqrt{2}\,B\,t\right)$$

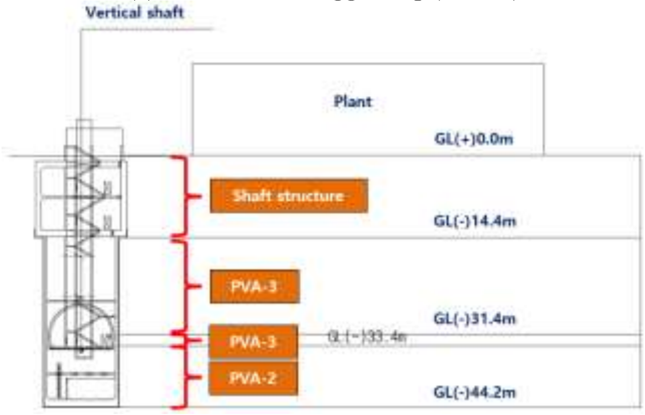
3.2 FE modelling

In this study, the subjects of dynamic numerical analysis are the gas turbine generator foundation, pump foundation, and DH pipeline. The specifications for each structure are summarized in Table 9 as follows.

The railway tunnel employs controlled blasting type 4 (CB4), consisting of advance of 1.0 m + Pre-Large Hole Boring Method(PLHBM) + Line drilling (L/D) to minimize the charge per delay and minimize the vibration propagation path. The vertical shaft tunnel has a circular shape with a diameter of 13.0 m, and at a depth of approximately 14.4 m from the surface, there is a ventilation structure. A vertical shaft tunnel is planned below it, with a vibration-free rock breaking method (PVA-3) applied from GL -14.4 to -31.4 m (section length 17m), controlled blasting (PVA-3, CB4) from GL -31.4 to -33.4 m (section length 2 m), and controlled blasting (PVA-2, CB4) from GL -33.4 to -44.2 m



(a) vertical shaft supporting (PVA-3)



(b) vertical section of shaft (PVA-3)

Fig. 4 Plan and section of vertical section

Table 10 Support systems of railway tunnel (CB4)

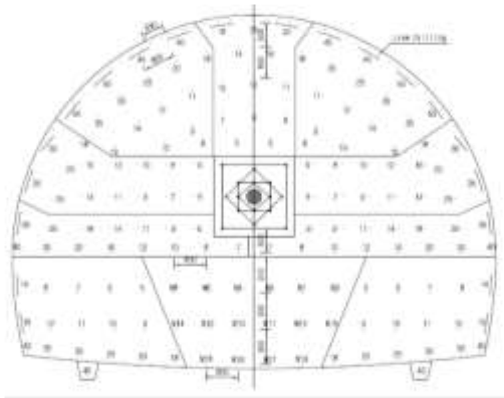
Support system			Railway tunnel
Advance(upper/lower)(m)			1.5 / 3.0
Supporting	Shotcrete thickness(mm)		Steel fiber reinforced shotcrete 120 (80/40)
	Rock bolt	Length(m)	4.0
		Longitudinal / Transverse(m)	1.5 /1.5
	Steel rib	Type	LG-50×20×30
		Spacing(m)	1.5
Concrete lining thickness(m)			350(reinforced)

(section length 10.8 m). The section and depth of vertical shaft are demonstrated in Fig. 4.

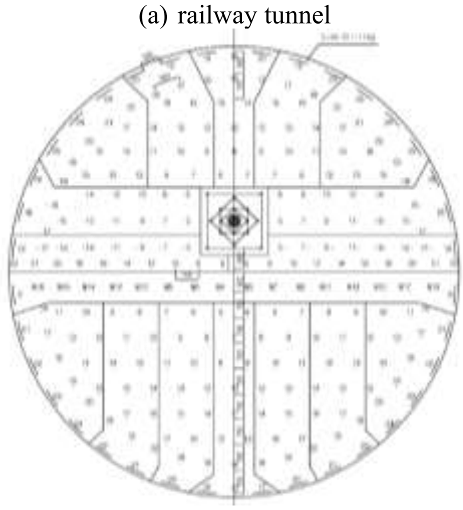
The support for the tunnel is divided into sections characterized by PVA-2 and PVA-3 from the top. The PVA-2 section utilizes steel rib (LG-50×20×30, CTC=1.2 m), steel fiber reinforced shotcrete (1st layer=80mm (21MPa), 2nd layer=40 mm (21 MPa)), and rock bolts (SD400, D25, L=4.0 m, CTC=1.2 m) as primary support, and the

Table 11 Support systems of railway tunnel (PVA-3)

Support system			Vertical shaft tunnel
Advance(upper/lower)(m)			1.0 / 1.0
Supporting	Shotcrete thickness(mm)		Steel fiber reinforced shotcrete 160 (80/80)
	Rock bolt	Length(m)	4.0
		Longitudinal / Transverse(m)	1.0 /1.0
	Steel rib	Type	LG-50×20×30
		Spacing(m)	1.2
Concrete lining thickness(m)			500(reinforced)



(a) railway tunnel

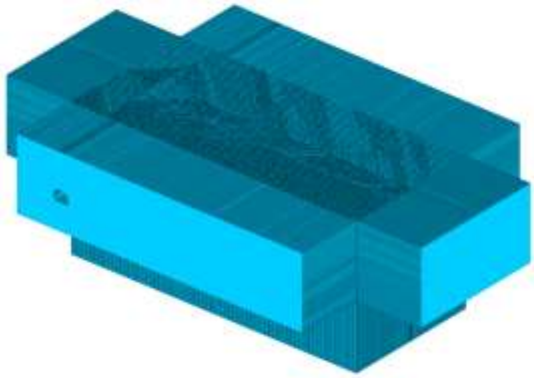


(b) vertical shaft tunnel (PVA-3)

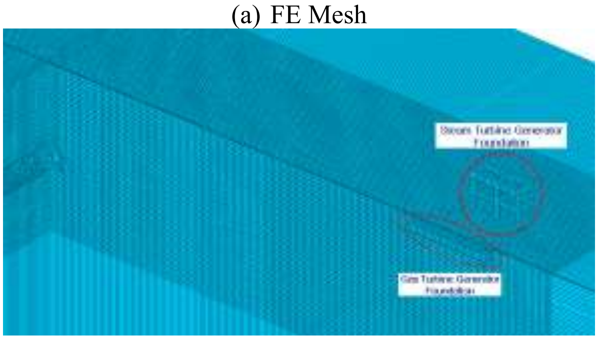
Fig. 5 Blasting patterns

secondary lining is designed with a thickness of 50 cm concrete (f_{ck} =27 MPa). The PVA -3 section employs steel rib (LG-70×20×30, CTC=1.0m), steel fiber reinforced shotcrete (1st layer=80 mm (21 MPa), 2nd layer=80 mm (21 MPa)), and rock bolts (SD400, D25, L=4.0 m, CTC=1.0 m) as primary support, with a secondary lining of 50 cm thick concrete (fck=27 MPa). The blasting patterns are described in the following Fig. 5, and support systems are summarized in Tables 10 and 11.

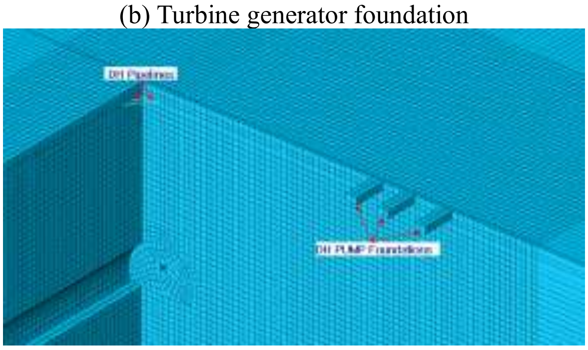
The number of charge holes in the railway tunnel (CB4) totals 191 (upper 137, lower 54), inducing delayed blasting through a combination of non-electric MS detonators and



(a) FE Mesh



(b) Turbine generator foundation

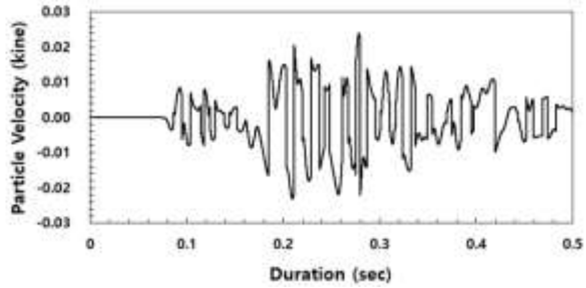


(c) Pump foundation and DH Pipelines

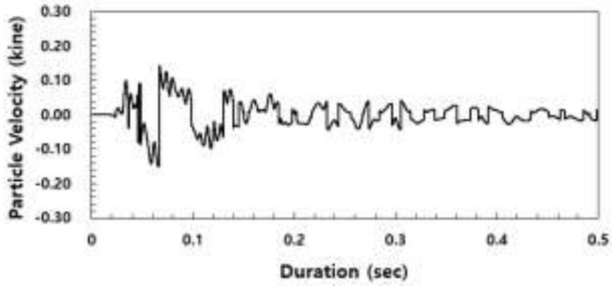
Fig. 6 FE modelling of each structure

non-electric LP detonators. The blasting area is divided into the center cut area, upper sections 1 to 7, and lower sections 1 to 3. In the center cut area, Pre-Large Hole Boring with unloading condition (102 mm diameter) is planned. The center cut area is in the central part of the tunnel cross-section with an area of 2.56 m². The charge per hole in the center cut area is planned to be 0.375 kg (8 holes) in Bench-1 and 2, and 0.375 kg (8 holes) in Bench-3 and 4, with a total planned charge of 6.0 kg.

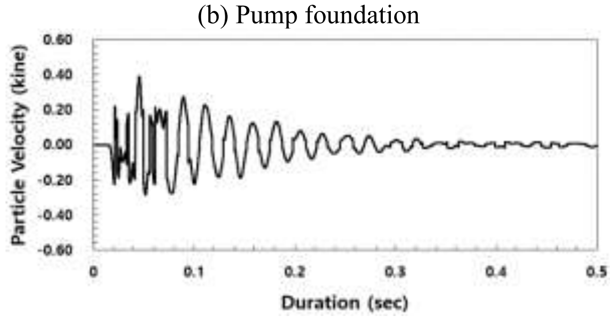
For the vertical shaft tunnel (PVA-3), the number of charge holes totals 307, inducing delayed blasting through a combination of non-electric MS detonators and non-electric LP detonators. The blasting area is divided into the center cut area, upper sections 1 to 9, and lower sections 1 to 8. In the center cut area, Pre-Large Hole Boring with unloading condition (362 mm diameter) is planned. The center cut area is in the upper central part of the tunnel cross-section with an area of 2.56 m². The charge per hole in the benching area is planned to be 0.5 kg (8 holes) in Bench-1 and 2, and 0.5 kg (8 holes) in Bench-3 and 4, with a total planned charge of 8.0 kg.



(a) Gas turbine generator foundation



(b) Pump foundation



(c) DH pipeline

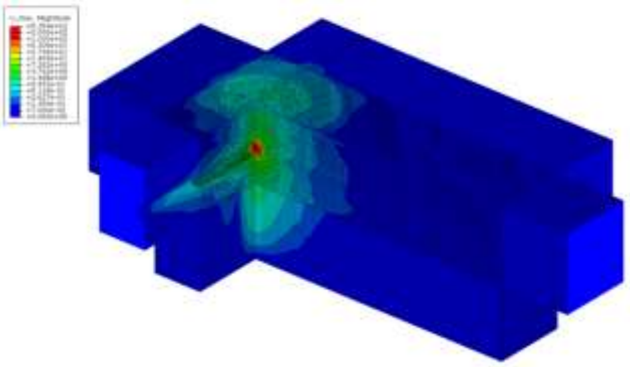
Fig. 7 PPV results at each structure

Based on this design, a 3D finite element mesh was generated. To ensure accuracy, the analysis model was composed of approximately 270,000 to 1.24 million elements depending on the size of the analysis domain. Infinite elements were applied at the lateral and bottom boundaries to minimize the influence of duplicate reflected waves. When an infinitely large area or object is included in dynamic numerical analysis, the modeling of this infinitely large area is achieved through infinite elements to reduce the computational workload and prevent distortions such as dynamic wave reflection and refraction at the boundaries. Additionally, hexahedral elements were employed to model and enhance the accuracy of the analysis results. The results are illustrated in Fig. 6.

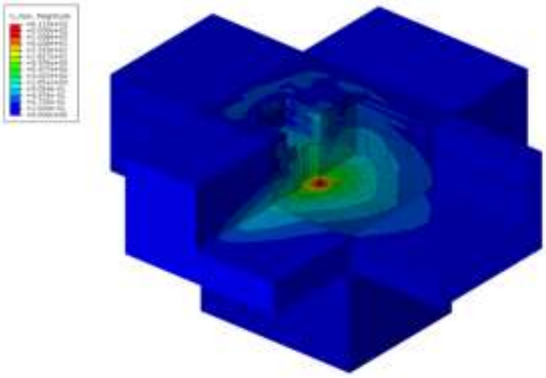
This analysis was conducted considering the characteristics of blast loads applied over an extremely short duration, utilizing elastic models for both the ground and structural components. It is noted that this analysis is based on the previous study showing that dynamic analysis provides a realistic response for ground and adjacent structures (Kim et al., 2020).

4. Analysis results

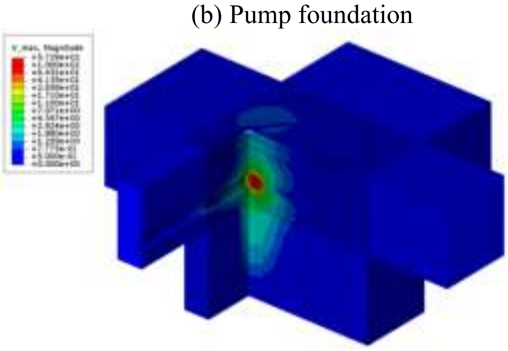
The results of the 3D dynamic numerical analysis were used to calculate the peak particle velocity at each



(a) Gas turbine generator foundation



(b) Pump foundation



(c) DH pipeline

Fig. 8 Dispersion of particle vibrations through the ground

foundation of the structures. The extent of damage due to seismic vibrations is typically represented using acceleration as a scale, considering displacement, velocity, and usually acceleration. However, in the case of blasting vibrations, the vibration frequency is significantly higher than seismic vibrations. Therefore, using acceleration as a criterion to represent the extent of damage is not appropriate, as the degree of damage due to vibrations can vary at the same acceleration value depending on the magnitude of the vibration frequency. This inadequacy arises from the inability to sufficiently express the vibrational characteristics solely based on acceleration values. In other words, as a method for considering the vibration frequency (or vibration period) characteristics as a criterion for assessing the stability of structures, it is more rational to examine the vibration velocity in the case of blasting vibrations. Additionally, vibration velocity has been found to have the best correlation in empirical observations regarding cracks induced by blasting (Sunwoo and Ryu, 2000). Therefore, globally, the permissible criteria for blasting vibrations are expressed in terms of the maximum vibration velocity, and the measurement and interpretation of blasting vibrations are generally conducted based on vibration velocity. In this study, to assess the impact of blasting vibrations, the method applied involves evaluating whether the maximum particle vibration velocity or blasting vibration velocity (PPV, Peak Particle Velocity) at the review location exceeds the permissible maximum particle vibration velocity or allowable blasting vibration velocity. The results for each structure are presented in Fig. 7. PPV was monitored at the surface of base mat in gas turbine generator and pump foundation. For DH pipeline, the bottom of the pipe is the monitoring point.

The peak particle velocity was calculated as 0.024 kine at the top of the gas turbine generator foundation, 0.149 kine at the top of the pump foundation, and 0.389 kine at the bottom of the DH pipeline, confirming that they are within the design criteria. The DH pipeline and pump foundation, being closer to the vibration source, exhibited a tendency for relatively uniform damping to occur after the imposition of blast loads. In contrast, the dynamic response of the gas turbine generator foundation, situated at a greater distance, showed irregular behavior and the magnitude of the peak particle velocity was small. Fig. 8 displays the dispersion of particle vibrations through the ground.

The three-dimensional dispersion of particle vibrations which were originated from the blast loading point can be observed. The application of infinite elements at the boundaries of the analysis model prevents the occurrence of duplicate reflected waves. Additionally, particle vibrations induced by blast loads are transmitted to the excavated tunnel walls and the surrounding ground. However, there is a noticeable trend of material damping and geometric decay as the distance from the analyzed structures increases. This is attributed to the effects of rapid geometric decay, material damping, and frictional resistance.

5. Conclusions

Suggestions

The peak particle velocity obtained from the 3D dynamic numerical analysis for blast-induced vibrations is calculated to be a maximum of 0.149 kine at the pump foundation. This result is close to the design criteria (0.15 kine) at a level of 99.3%. Additionally, for the DH pipeline, the peak particle velocity is calculated to be 0.389 kine, which is also close to the design criteria (0.4 kine) at a level of 97.3%. The DH pipeline is located at the upside vicinity of the blast vibration source (distance approximately 26.7 m) and is connected to the external network, supplying heat to the entire city, making it extremely critical. Moreover, the DH pipeline has been buried for a considerable period, and its burial depth and distance from the crown of the railway tunnel are approximately 2.5 times the tunnel cross-sectional diameter, emphasizing the need for careful consideration before blasting.

Therefore, considering the importance of the DH pipeline, construction uncertainties, the magnitude of the peak particle velocity at each structure, a more conservative tunnel excavation method is desirable. Accordingly, the following alternatives are suggested:

• Apply vibration-free rock breaking method for the entire section passing beneath the plant to minimize risks.

• Implement active vibration measurement during construction by continuously monitoring blast-induced vibrations. If the vibration approaches 95% or more of the design criteria, consider changing the blasting pattern (e.g., controlled blasting using precision explosives and electronic detonators, reducing advance, etc.).

• The design criteria for blast-induced vibrations have been proposed by comprehensively considering the significance of the relevant equipment, the sensitivity of high-speed rotating machinery, and the assurance of operational stability. Applying the ISO 10816-1 Class II standards for high-speed rotating machinery, a criterion of 0.15 kine has been suggested. For the heat transport pipe, in accordance with the standards of the Korea District Heating Corporation, a maximum vibration velocity of 0.4 kine is applied.

• 3D dynamic numerical analysis results for blast-induced loads indicate that the peak particle velocity at the pump is 0.149 kine, very closely approaching 99.3% of the design criteria of 0.15 kine. Similarly, for the DH pipeline, the calculated particle velocity of 0.389 kine is at a level of 97.3% of the design criteria of 0.4 kine. Therefore, considering the significance of the plant, it is proposed to apply the vibration-free rock breaking method for the entire section passing beneath the plant.

To supplement the limitations of numerical analysis, a real-time monitoring system is suggested to be established to continuously and automatically measure vibrations caused by blasting. If the measured vibration velocity exceeds 95% of the design criteria of 0.15 kine, it is recommended to temporarily stop the blasting operations and implement additional corrective methods. Additionally, during blasting, meticulous construction management must be implemented to ensure accurate blasting according to the design drawings. Specifically, measures such as prevention of excessive blasting and prevention of over-excavation. Reducing the charge per delay and decreasing advance might be appropriate solutions.

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