



Seismic Damage and Possible Influencing Factors of the Damages in the Melamchi Tunnel in Nepal Due to Gorkha Earthquake 2015

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Abstract Nepal is a sensitive earthquake zone. On April 25, 2015, there was an Earthquake of 7.8 Mw. After that, more than 30 aftershocks of above 5 Mw occurred. One of the aftershocks was of 7.3 Mw which occurred on May 12. In this paper, the damages in the tunnel of the Melamchi water supply project due to this earthquake were assessed. Cracks were observed on the inside surface, wall, and crown of the tunnel. Distribution and characteristics of these seismic damages were investigated and summarised to assess potential influencing factors. The damages are categorized into the following patterns: lining cracks and spalling. Lining cracks are further divided into longitudinal cracks, transverse cracks, ring cracks, and inclined cracks. Influencing factors are discussed with

respect to Earthquake parameters mainly being magnitude, depth and distance to epicenter. This paper presents the pattern of seismic damages occurred for different overburden depths and different rock types. Here, the analysis is done by observation and categorization of damages for different aspects of considered factors and there are some unusual results in damages for varying overburden depths. There were few unusual results as in the damage distribution for overburden depth and also for different rock types. The reason may be the occurrence of many considerable aftershocks and epicenter being very near, so the damages may have been accumulated after each shock. Also the distribution of rock types have influenced the damages. So one influencing factors may have its effects on the results while considering the other factor.

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1 Introduction

Gorkha earthquake 2015 was one of the most devastating earthquakes. During this earthquake, many above-ground structures were damaged and also there were quite a few damages in underground structures.

The water conveyance tunnel of “Melamchi water supply project” was one of them. The damages provide sufficient evidence to suggest that the safety of tunnel in seismically active areas is still an important issue, but not well understood yet, or at least not well considered during design. Nevertheless, however badly the tunnels were damaged, they remained relatively intact when compared to surface structures.

Many researchers have studied about the structural behavior of mountain tunnels with respect to seismic loading. Dowding and Rozan (1978) made a database of 71 tunnels in which damage occurred due to the earthquake. Different levels of damage were reported, ranging from cracks to closure, in 42 tunnels. Sharma and Judd (1991) made a database in which they compiled the response of 192 tunnels considering 85 different earthquakes throughout the world; among them, 94 of the tunnels had damages ranging from small to heavy. A large number of case histories were collected by Asakura and Sato (1998), in which they observed the mountain tunnels in Japan which were subjected to earthquakes; 124 of the tunnels exhibited different levels of damages; 53 of them had heavy damage. Wang et al. (2001) provided an assessment of the damages in mountain tunnels due to the chi-chi earthquake; of the 57 tunnels investigated, 49 were damaged. Chen et al. (2012) studied 81 mountain tunnels that were damaged in 10 recent strong earthquakes.

It was widely accepted that the mountain tunnel was assumed to be seismic resistant due to being situated deep within rocks layers (Towhata 2008). Whereas, three strong earthquakes; the 1995 Kobe earthquake, the Chi-Chi earthquake and the 2008 Wenchuan Earthquake have given strike on this traditional view. Among them, in the Kobe Earthquake, 12% of mountain tunnels in the epicentral area were damaged severely (Yashiro et al. 2007); in the Chi-Chi Earthquake, 26% of 50 tunnels located within 25 km of the earthquake fault were damaged heavily and 22% were moderately damaged (Wang et al. 2001) and In the Wenchuan Earthquake, 73% of 18 tunnels located in the Du(Du-Jiang-yan)- Wen(Wen-Chuan) highway were severely damaged and 22% were damaged moderately (Wang et al. 2009). The damages to mountain tunnels, by earthquakes that occurred in recent years, have attracted much higher attention on seismic effect on mountain tunnels.

The main factors affecting the damage to tunnels are earthquake magnitude, epicentre distance, depth of epicentre, duration of the earthquake, overburden depth, types of rock, and cross-section of tunnel. The current design codes for seismic design of mountain tunnels focus on the stability of the portals and the sections of the tunnel near slope surfaces but do not consider potential damages that may occur at other sections of tunnel, except for ground failure (Wang et al. 2001). This conclusion serves as a warning for the need for better design of tunnels and other underground structures in seismic areas.

This paper describes in detail the damages observed in the Melamchi tunnel, which was affected by Gorkha earthquake 2015, Nepal. And statistical analysis was done considering different influencing factors.

2 Project Area

This project consists of 26.3 km long tunnel with 3 audits and intake structures. Maximum overburden depth is about 1150 m. Including the three audits, namely Ambathan, Gyalthum and Sindhu, access was provided to seven working areas along the tunnel alignment. The theoretical cross-sectional area of the tunnel is 12.7m² (EDCO 2001). Drill and blast techniques are adopted for tunnel excavation (Bhattarai -Executive et al. 2015). A strict accounting system is in place for explosives. Figure 1 shows the typical section of Melamchi Tunnel.

In the Sundarikal-Melamchi area(the project area), the higher Himalayan crystalline contain large masses of augend and banded gneisses, and also record a relatively higher grade of metamorphism than their corresponding formations included under the Kathmandu Complex. The rocks comprise the northeast limb of the Mahabharat synclinorium and part of the Gosainkund tectonic bridge (Dhital 2015). Most of the rocks are strongly foliated and hence anisotropic in strength. Geological formation along the tunnel have been assessed from the intake to outlet as:

- Timbu Formation, 0–6.6 km in tunnel, with migmatite (60–70%) and banded gneiss (10–15%), intensely deformed and folded, with subordinate quartzite (10–15%) and schist (5–10%).

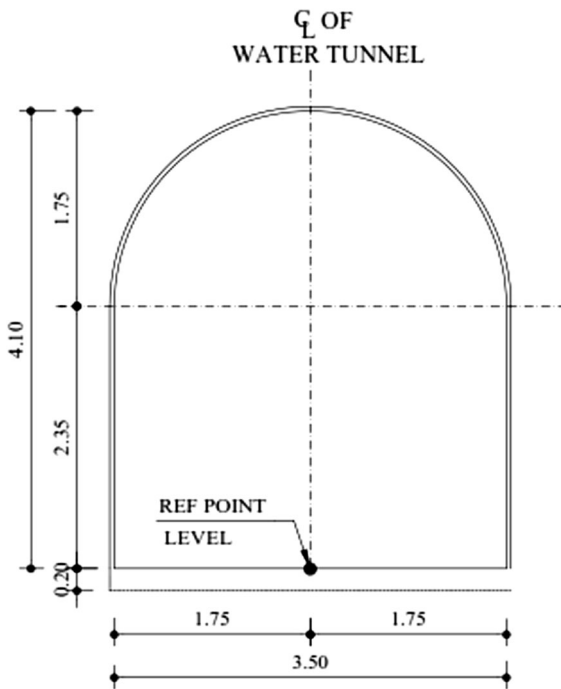


Fig. 1 Typical Section of Melamchi Tunnel; Unit m

- Bolde quartzite, 6.6–8.2 km in tunnel, with alternation of laminated quartzite and banded schist
- Gyalthum Formation, 8.2–19.5 km in tunnel, with alternation of laminated or cross-bedded quartzite and banded schist. The quartzites are intensely deformed leading to many conspicuous small-scale folds and faults.
- Shivapuri injection Gneiss zone, 19.5–26.3 km in tunnel, with banded gneiss (80–85%), augen gneiss (10–15%) and granitic gneiss (5–10%)

Figure 2 shows the longitudinal profile of the tunnel with geological formation. The location map of tunnel with epicenters of main earthquake and May 12th aftershock is shown in Fig. 3.

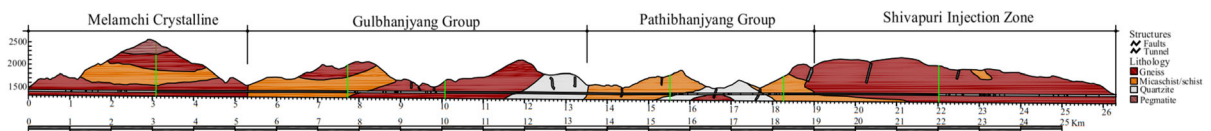


Fig. 2 Longitudinal profile of the tunnel

3 Overview of the Gorkha Earthquake, 2015 and Seismic Damages to the Tunnel of Melamchi Water Supply Project

3.1 Overview of the Gorkha Earthquake

The Gorkha Earthquake on 25th April, 2015 had the epicenter depth of approximately 15 km which is considered as shallow and therefore more damages occurred than those due to quakes that originate deeper in the ground. The epicenter was at a distance of 80 km to the northwest of Kathmandu, the capital city of Nepal and it lasted for approximately 50 s (Goda et al. 2015).

The first main quake was measured as 7.8 Mw. The second earthquake was somewhat less powerful at 6.6 Mw, it occurred 65 km east of Kathmandu and its epicenter depth was 10 km. Over thirty-eight aftershocks of magnitude 4.5 Mw or greater occurred in the days following the initial earthquake, including the one of magnitude 6.8 Mw.

Another major earthquake occurred on 12th May 2015 with 7.3 Mw, 18 km southeast of Kodari. The epicenter was on the border of Dolakha and Sindhupalchowk, two districts of Nepal. This earthquake occurred on the same fault as the larger magnitude 7.8 Mw earthquake of 25th April. As such, it is considered to be an aftershock of the 25th April quake and its depth is 18.5 km (Aydan and Ulusay 2015). List of main quake and aftershocks are shown in Table 1.

Location of the main quake and aftershocks, and the location of the tunnel are shown in Fig. 4(USGS) and the graph of the main quake and aftershocks are shown in Fig. 5(USGS).

3.2 Seismic Damages to the Tunnel of Melamchi Water Supply Project

The Melamchi water conveyance tunnel is 26.3 km long. Head race—Melamchi portal—is 83.88 km far from epicenter of 7.8Mw earthquake and 55.55 km far from epicenter of 7.3 Mw earthquake. And the

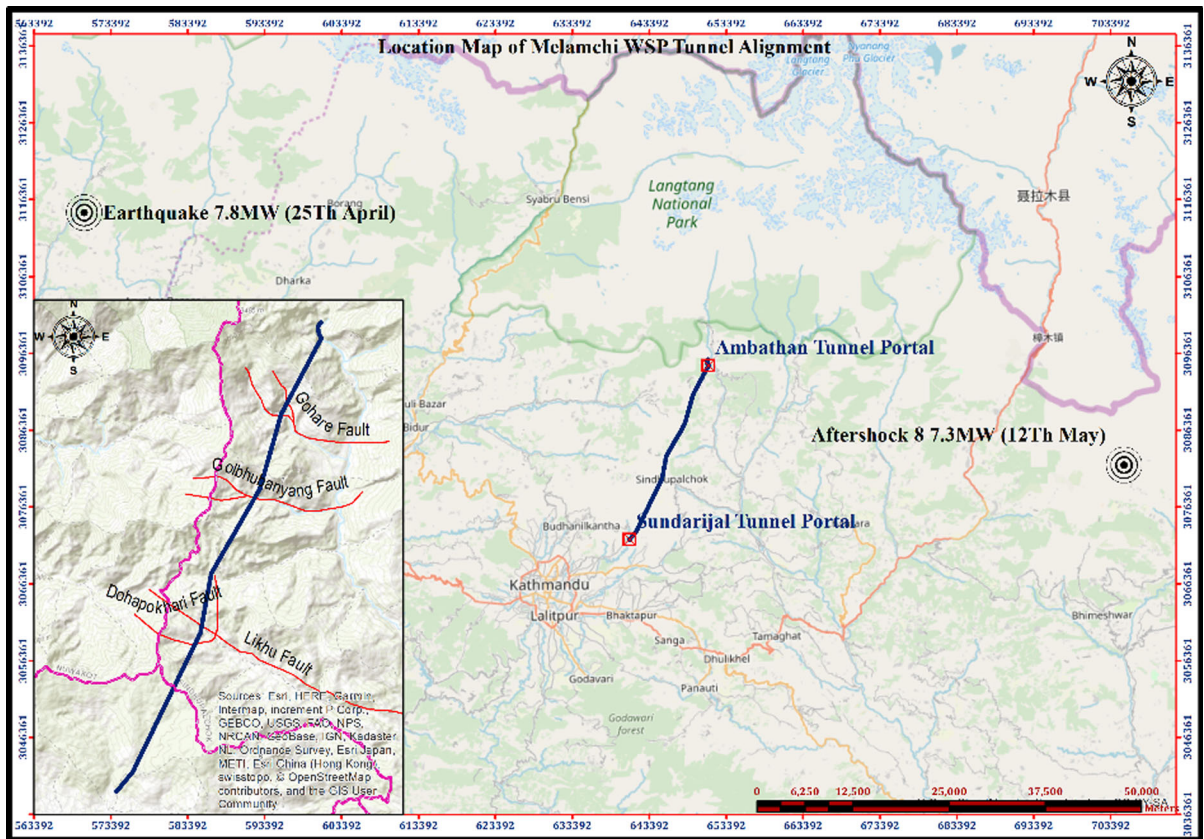


Fig. 3 Location of the Melamchi tunnel and epicenters of the Gorkha earthquakes 2015

Table 1 List of main quake and aftershocks of magnitude 5.0 and higher recorded at Kathmandu by USGS

	Date	Magnitude	Depth (km)	Distance from Ambathan tunnel portal(km)	Distance from Sundarijal tunnel portal(km)
Main	25th April	7.8	15	83.330	82.670
Aftershock 1	25th April	6.6	14.6	69.569	72.541
Aftershock 2	25th April	5.5	10	13.325	27.510
Aftershock 3	25th April	5.3	10	36.799	15.224
Aftershock 4	25th April	5.4	10	39.625	64.809
Aftershock 5	25th April	5.6	10	67.685	55.145
Aftershock 6	26th April	6.7	17.6	50.611	56.557
Aftershock 7	26th April	5.3	10	33.012	33.842
Aftershock 8	12th May	7.3	15	55.766	64.982
Aftershock 9	12th May	6.3	15	73.841	74.979

Source:(USGS) strong motion center

tailrace—Sundarijal portal—is 85.5 km far from epicenter of 7.8Mw earthquake and 64.7 km far from epicenter of 7.3 Mw earthquake.

The Melamchi tunnel, one of the damaged tunnels during the 2015 Gorkha earthquake, had small to heavy damages. The damage along the tunnel,

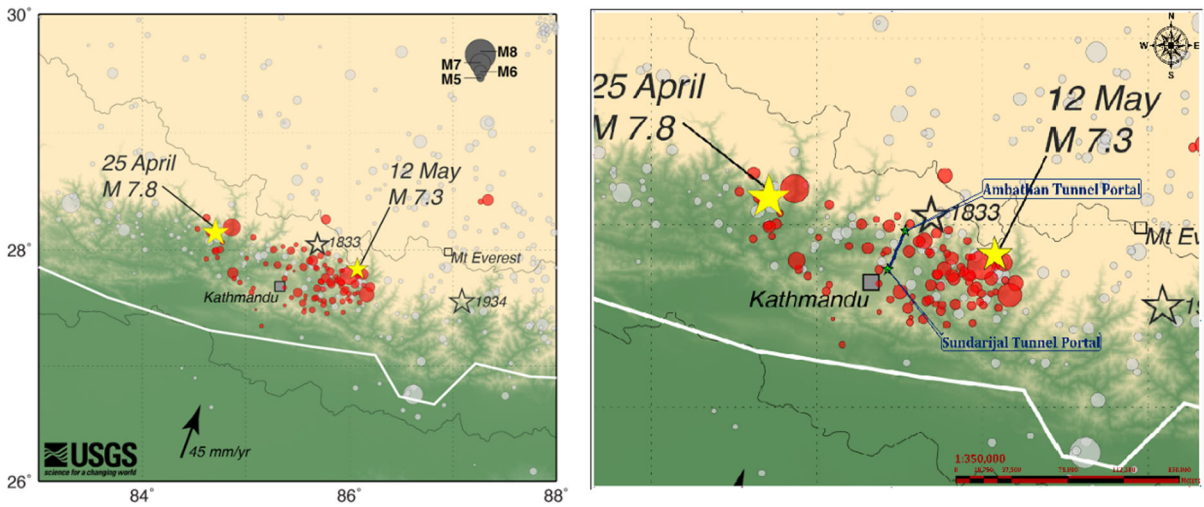


Fig. 4 Map of main quake, aftershocks and location of tunnel

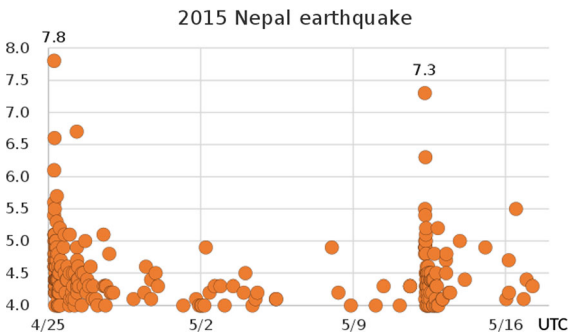


Fig. 5 Main and aftershocks of 2015 Gorkha earthquake

according to the field investigation, is described in detail later. We start from headrace of the tunnel. At the headrace, there was slope failure. The interior of the tunnel also suffered significant damage. There are longitudinal cracks, vertical cracks, and even cracks in the crown. In some places, the steel reinforcement was also exposed. There were many damages which needed retrofitting. The Melamchi water conveyance tunnel suffered from small to heavy damages both at the portal and inside of the tunnel. The location of damages on the project, in detail, are shown in Fig. 6.

4 Classification of Seismic Damages

4.1 On the Basis of Degree of Damages

The Standard damage classification is not available yet. Dowding and Rozan (1978) considered three damage classes (i.e. no damage, minor damage and damage) based on the crack width and length. Huang et al. (1999) and Wang et al. (2001) modified Dowding and Rozen’s classification by subdividing the minor damage to slight damage and moderate damage. Following the 2008 Wenchuan earthquake, extremely severe damage to tunnels, including lining collapse and dislocation, have been reported (Wang and Zhang 2013). Shen et al. (2014) classify damage into four levels; no damage, slight damage, moderate damage and extreme damage. Based on the literatures mentioned above, in this paper damages are classified into 3 levels (Table 2). Slight damage (SI), moderate damage (M) and Severe damage (Se).

From site observation the damage at some places were noted as damage, at some places noted as damages and some places noted as several damages. It would be misleading to give same number to damages at different places. So, for the analysis in this paper the damage count was modified to as: 1 for ‘damage’, 2 for ‘damages’ and 5 for ‘several damages’ (Table 3). Thus it was considered as representative number of damages as per in the site, and this was used for analysis.

Some damages found in Melamchi Tunnel are shown in Figs. 7,8 and 9.

From the observation result, it was found that 51.85% of total damages were slight damages, 28.70% were moderate damages, and 19.45% were severe damages. So, here slight damages were maximum and severe were the minimum. Distribution of damage degree is shown in Fig. 10. Past studies also show that the slight damages in tunnels are more than severe damages. In some earthquakes, (Asakura and Sato 1998), about 50% of tunnels needed reinforcement and repair because these tunnels were very near to epicentre and epicenter-depth was also less.

4.2 On the Basis of Types of Damages

Various patterns of seismic damages in the Melamchi Tunnel caused by 2015 Earthquake were observed Figs. 11,12 and 13. Some of the major patterns were

Table 3 Degree of damages in the tunnel

Damage degree	Counts of damages	Percentage of damages
Sl	112	51.85
M	62	28.70
Se	42	19.45

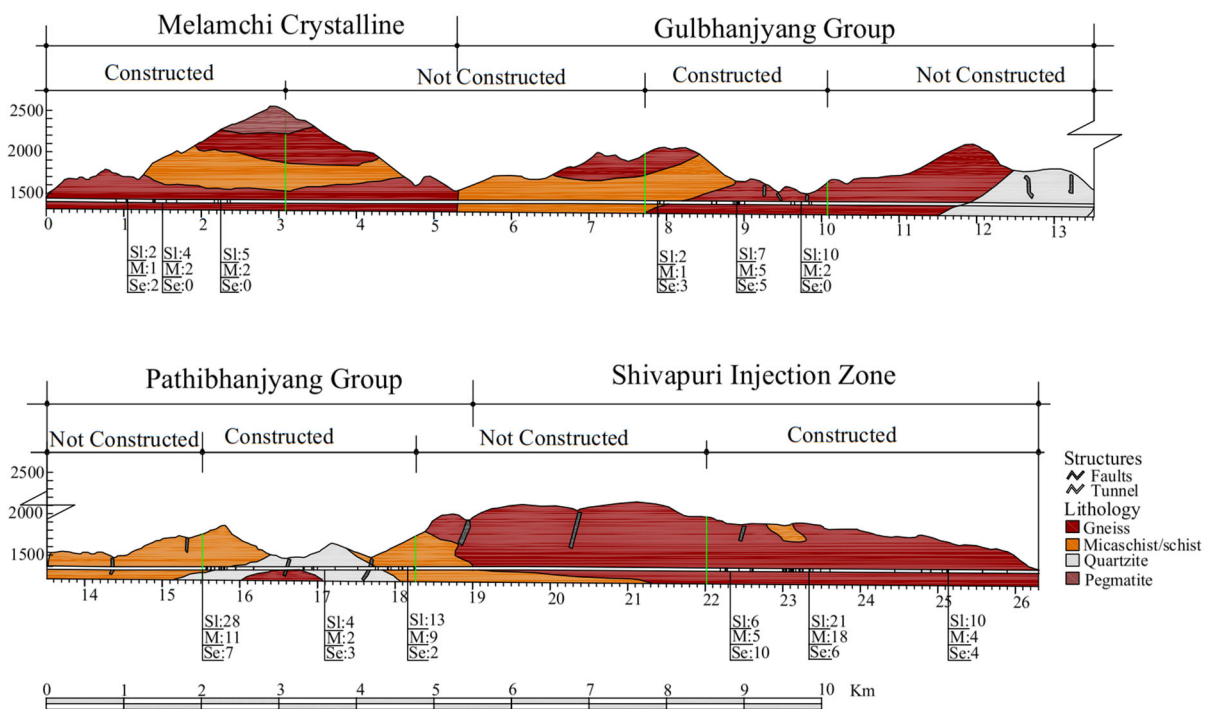


Fig. 6 Longitudinal profile and damage locations of Melamchi tunnel

Table 2 Classification and description of the degree of damages

Damage level	Damage description
Slight (Sl)	Slightly damage, lining cracking $W < 3$ mm, $L < 5$ m, No restoration needed
Moderate (M)	Local small scale spalling and reinforcing steel bar exposed, lining cracking $3 \text{ mm} < W < 30$ mm, $5 \text{ m} < L < 10$ m. Compromised functionality. Need restoration
Severe (Se)	Large scale spalling and reinforcing steel bar exposed and distorted, lining cracking $w > 30$ mm, $L > 10$ m



Fig. 7 Sight damage



Fig. 8 Moderate damage

illustrated and their potential influencing factors were also discussed.

Among all the damages 86.57% were lining cracks and 13.43% were spalling. Lining cracks are the most frequent type of damage to tunnels caused by earthquakes. Lining cracks are further divided into ring cracks, longitudinal cracks, transverse cracks and inclined cracks. Transverse cracks are perpendicular to the direction of the tunnel axis and inclined cracks with inclination of 40–70°(Zhang et al. 2018). Among 86.57%, 5.56% are ring cracks, 24.54% are longitudinal cracks, 38.43% are transverse cracks and 18.04% are inclined cracks. Seismic damage distribution of tunnel is shown in Fig. 14 and Table 4.

As illustrated in the above table and Fig. 14, the observation was made to identify the severity of



Fig. 9 Severe damage

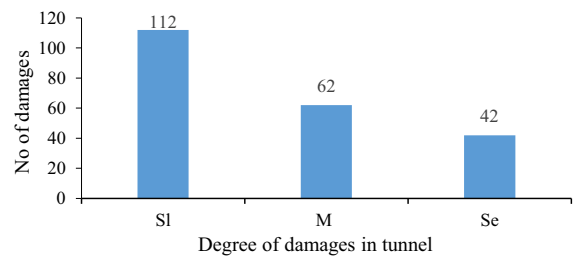


Fig. 10 Degree of damages in tunnel



Fig. 11 Lining crack, up to 7 mm at chainage 18 + 239



Fig. 12 Spalling, shotcrete fall from right wall along shear band, area up 1sqm at chainage 16 + 823



Fig. 13 Ring crack, several shotcrete cracks observed along the crown and both walls with opening up to 1.50 cm at chainage 15 + 937

damages in all different types of damages. And thus we can see that in spalling, severe damages were very little as compared to slight and moderate. In-ring cracks, severe damages were much higher than the other two. In longitudinal cracks, slight damages are more, almost half of them, than the other two. In transverse cracks, slight damages are much more, about two-thirds and severe damages were very few. In inclined cracks also slight damages were more, about half of them, and gradually followed by moderate and then severe the least. Here we can see that all of the damages has a lower percentage of severe barring one damages and more of slight damages, the ring cracks had much more severe cracks.

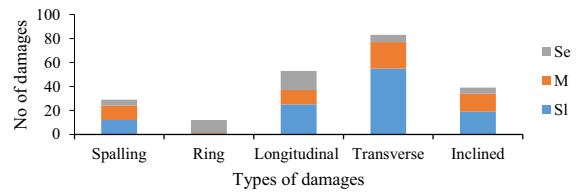


Fig. 14 Seismic damage distribution of tunnel

5 Influencing Factors

5.1 Earthquake Parameters

With regards to the influence on structural damage, earthquake parameters mainly consist of magnitude, depth of earthquake source, epicentral distance and shaking duration. In conjunction, these four factors determine the earthquake intensity in a particular area: with a higher magnitude, shallower epicentre depth, shorter epicentral distance, longer shaking duration, the earthquake will be more intense in the area and exert a stronger influence (Hashash et al. 2001). Okamoto and Tamura (1972) concluded after the study of seismic tunnel damage in Japan, that the tunnels over 50 km far from the epicentre do not get influenced. And in this project, head race -Melamchi—portal is 83.88 km far from epicenter of 7.8Mw earthquake and 55.55 km far from epicenter of 7.3 Mw earthquake. And the tailrace, Sundarijal portal is 85.5 km far from epicenter of 7.8Mw earthquake and 64.7 km far from epicenter of 7.3 Mw earthquake. Acceleration waves measured during main shock and 12th May aftershock are shown in Figs. 15 and 16 respectively.

5.2 Overburden Depth

The overburden depth varied from 0 to 1100 m so it was grouped into 3 categories for observation: shallow depth tunnel 0–300 m, medium depth tunnel 300–700 m and Deep tunnel 700–1100 m, and the no. of damages per km for that overburden depth were taken (Tables 5 and 6). It was found that for overburden depth of 0–300 m there were 7.36 damages per km, for 300–700 m it was 31.17 and for 700–1100 m it was 4.01. From this, we get a pattern of damage occurrence. Here we can see that for high overburden depth (700–1100 m) the damages are very

Table 4 Seismic damage distribution of tunnel

Degree of damages	Spalling		Ring		Longitudinal		Transverse		Inclined	
	No.	%	No.	%	No.	%	No.	%	No.	%
SI	12	41.38	1	8.33	25	47.17	55	66.27	19	48.72
M	12	41.38	1	8.33	12	22.64	22	26.51	15	38.46
Se	5	17.24	10	83.33	16	30.19	6	7.23	5	12.82
Total	29		12		53		83		39	

low as compared to lower overburden depths—0–300 m and 300–700 m.

There are general findings from previous researches or theories that there are more damages to areas of less overburden depth. But here we see that the damage for 300–700 higher than that in 0–300 m which is peculiar. This could also be because of other influencing factors such as type of rock, rock support class etc. As can be seen in other discussions, different rock types has different damage density. So it needs detail observation and analysis of particular rock type for corresponding overburden depth.

Here we can see the detail inspection of damages for different overburden depth and the occurrence of different degree of damages are obtained. In all of these half or more than half are slight damages, and then moderate and severe damages are very low in percentage.

As expected for very high overburden depth there is less damage, for 700–1100 m there are no severe damages at all and the highest proportion for severe damage is for 0–300 m being 22.27%. Figure 17 shows damages with respect to overburden depth.

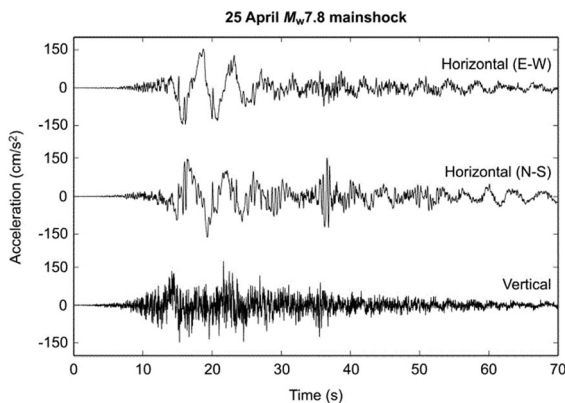


Fig. 15 Wave acceleration measured at KNTF station during 25th April mainshock

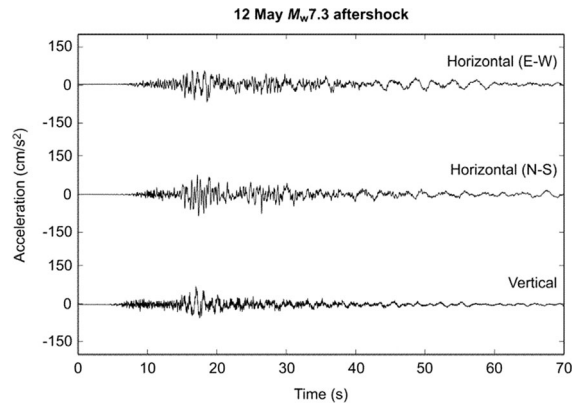


Fig. 16 Wave acceleration measures at KNTF station during 12th May aftershock

5.3 Rock Support Class

The design of rock support is based on the Q-system (Barton et al. 1974). Based of rock quality it was divided into six different support types (Fig. 18 and Table 7). There were class I, II, III, IV, V & VI in which class I is the strongest and VI is the weakest.

Here, the Q value for IVA and IVB is the same and decided as per site condition, for example, if we encountered clay band, more joints, slabbing in the crown, and water seepage, then it comes under IVB. General consideration was that IVA is gneiss and IVB is schist.

The no. of damages per 100 m of each class of rock were calculated as shown in the Table 8 and used for analysis and comparison. From this, we can observe that the occurrence of damages is pretty similar for different classes of rocks, with class IVB showing the most damage. One reason for this can be the fact that, for weaker rocks, various stabilizing measures (such as lattice girder and rock bolting) were taken while constructing the tunnel.

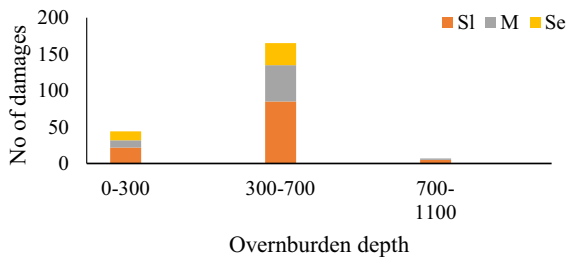
The Table 9 shows the severity of damages in each rock class. From this, we can see the extent of damages

Table 5 Damages in tunnel with respect to overburden depth

Overburden depth (m)	Length of tunnel (km)	Counts of cracks	% of cracks
0–300	5.976	44	7.36
300–700	5.294	165	31.17
700–1100	1.745	7	4.01

Table 6 Degree of damages with respect to overburden depth

Damage degree	0–300		300–700		700–1100	
	No.	%	No.	%	No.	%
SI	22	50.00	85	51.52	5	71.43
M	10	22.73	50	30.30	2	28.57
Se	12	27.27	30	18.18	0	0.00
Total	44		165		7	

**Fig. 17** Damage in tunnel with overburden depth

in each rock class and percentage of different level of damages. In class II very high percentage of slight damage occurred with a little moderate and no severe damages, in class III the most is moderate and little lower the slight and severe is the least but there is not a vast difference, in class IVA slight damages are the most and moderate and severe are almost same and little lower than the slight, in class IVB a very high percentage are slight and very little the other two, in class V also a very high percentage is slight and then lower moderate and no severe damages, and in class VI very little damage was found and they were only moderate.

In Fig. 19, we see that big portion of the damages are slight damages and then decreasingly moderate and then severe in almost all types of rock which is obvious. There are few exceptions as in class III, and class VI moderate is higher. This can be due to various

aspects as the location in the tunnel and the state of the tunnel as stabilized for construction. And for class VI there was very little portion of this rock, and hence very little damages, so cannot be concluded on pattern of damage occurrence (it was only 88 m and only 2 damages).

5.4 Rock Type

The study area comprised of 3 types of rock and they were Gneiss, Micaschist/Schist and Quartzes. The damages for each kind of rock were calculated in per km basis to compare all of them. The damages per km for each rock type is calculated and shown in the Table 10. We can see that the damage density in Gneiss is much less than that in the other two. And Micaschist/schist has the highest damages per km followed by Quartz.

Here in Table 11 and Fig. 20, the damages occurred in different types of rocks are further observed in detail and categorized by the degree of damage. This shows that in all the rocks the slight damages comprise the highest percentage. In Gneiss and Micaschist the slight damage is much more (nearly 50% and more than 50%) while in quartz it is even for all degree of damages with slight about 45% and the other two about 30%. This shows that the occurrence different degree of damages may also depend on the rock type, making it an influencing factor.

6 Discussion

From the assessment of damages caused by 2015 Nepal Earthquake on the tunnel of Melamchi water supply project, the observation and analysis of damages were done on the basis of different criteria. From the observation result of this study it can be seen that degree of damages and types of damages in general are similar to those from past studies in most parts of the

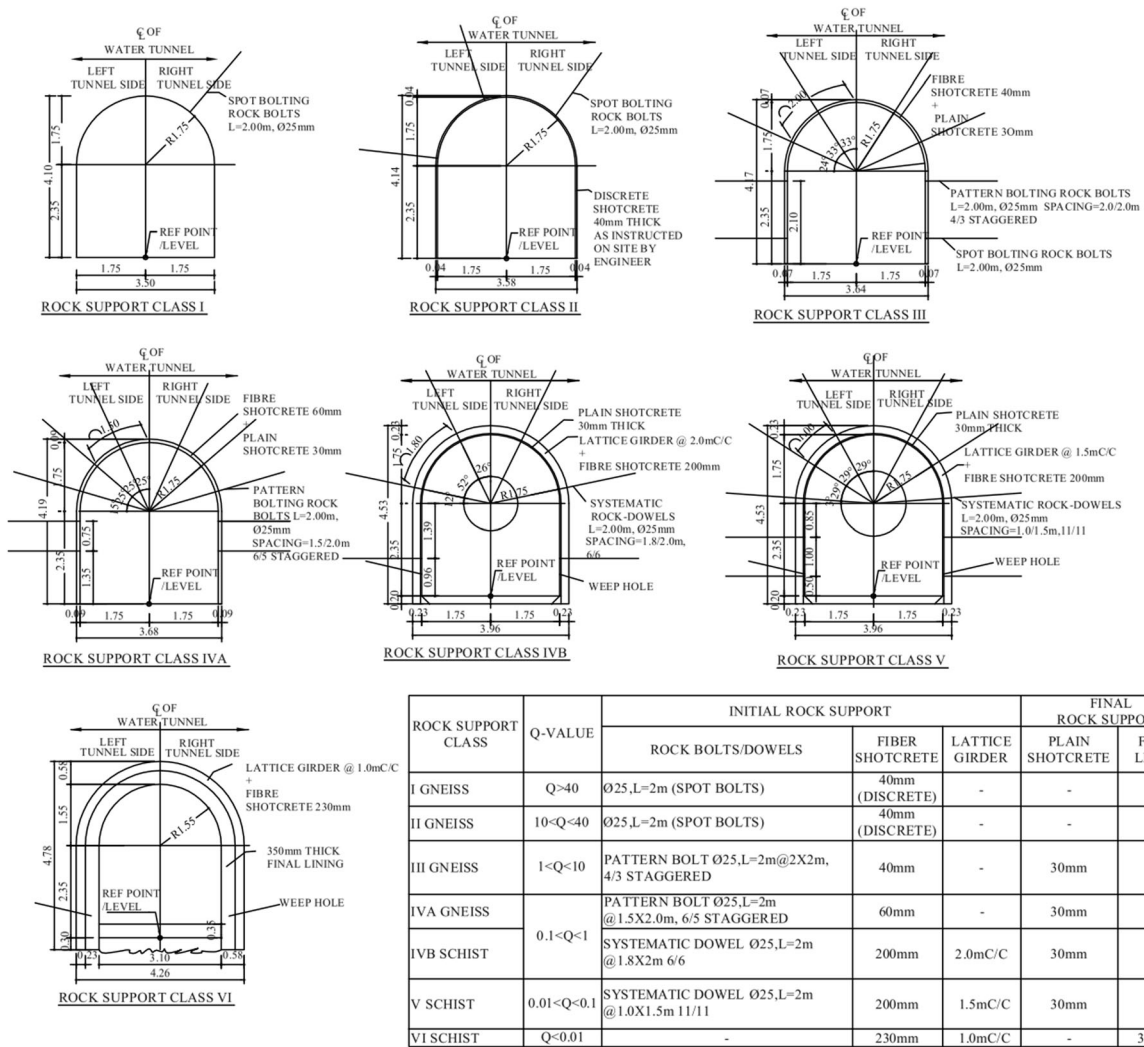


Fig. 18 Rock support class

Table 7 Description of rock support type

Rock support class	Q-value	Rock mass condition	Support type
I	$Q > 40$	Very good	Discrete shotcrete and rock bolts
II	$10 < Q < 40$	Good	Discrete shotcrete and rock bolts
III	$1 < Q < 10$	Fair	Shotcrete, steel ribs and patterns bolting
IVA	$0.1 < Q < 1$	Poor	Shotcrete, steel ribs and patterns bolting
IVB	$0.1 < Q < 1$	Poor	Shotcrete, steel ribs and systematic dowel
V	$0.01 < Q < 0.1$	Very Poor	Shotcrete, steel ribs and systematic dowel
VI	$Q < 0.01$	Very Poor	Reinforced concrete lining

tunnel (Rajyaswori et al. 2020). Many quakes occurred in the nearby areas of the study site. And also various aftershocks occurred with epicenter being near and of

low depth. The damages in the tunnel were the result of these earthquakes and aftershocks. The fact that a number of aftershocks occurred in the periphery of the

Table 8 Damages in tunnel with respect to rock support type

Rock support class	No. of damages	Length	Damage per 100 m
II	18	723.2	2.49
III	60	4454.7	1.35
IVA	89	4134.7	2.15
IVB	31	647.78	4.79
V	16	1322.22	1.21
VI	2	88.1	2.27

Table 9 Degree of damages with respect to rock support type

Damage degree	II		III		IVA		IVB		V		VI	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
SI	16	88.89	20	33.33	36	40.449	28	90.32	12	75	0	0
M	2	11.11	25	41.67	27	30.337	2	6.45	4	25	2	100
Se	0	0.00	15	25.00	26	29.213	1	3.23	0	0	0	0
total	18		60		89		31		16		2	

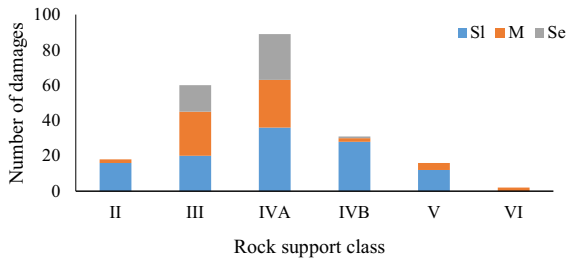


Fig. 19 Damages with respect to rock support class

tunnel may have caused the occurrence of damages in unusual pattern and severity. As seen in the results for damages observed on the basis of overburden depth, rock support type there were unusual patterns of

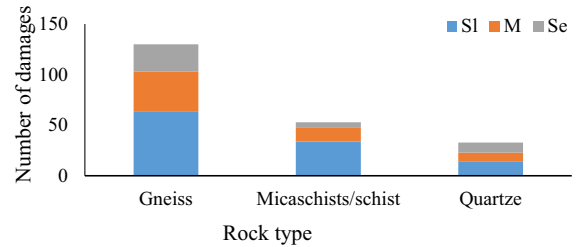


Fig. 20 Degree of damages with respect to rock type

damages in some parts of the tunnel which were different according to the rules or theories given by previous studies.

Generally the damages in the tunnels with lower overburden depth have more damages than in higher

Table 10 Damages in rock type

Rock type	Length(km)	No. of damage	Percentage of damage
Gneiss	9.808	130	13.25
Micaschists/ schist	1.349	53	39.29
Quartze	2.185	33	15.10

Table 11 Degree of damages in rock type

Damage degree	Gneiss		Micaschists/schist		Quartz	
	No.	%	No.	%	No.	%
SI	64	48.48	34	64.15	14	45.16
M	39	29.55	14	26.42	9	29.03
Se	27	20.45	5	9.43	10	32.26
Total	130		53		33	

overburden depth. But, here from the observation and study of damages according to overburden depth, we found that the damages in the areas of 300–700 m depth (31.17%) are more than those in 0–300 m depth (7.36%) which is unusual. The reason for this can be the occurrence of many considerable aftershocks and also the rock types present in those areas as rock types also can affect the occurrence of damages. For further observation of results, numerical analysis can be done considering different overburden depths for particular rock types and the results can be compared for further study.

For the results of damages according to different rock support type it shows that, damages per 100 m of class II is 2.49, class III is 1.35, class IVA is 2.15, class IVB is 4.79, class V is 1.21 and class Vi is 2.27. The damages occurred are varying in pattern from previous studies. So it is required to study further in detail for certain rock types in the site and hence find some new results. The results may also have been different because of complex rock structures and orientation in the site which can be further studied in detail.

7 Conclusion

Various damages occurred in the Melamchi Tunnel. The damages were categorized into different types and various factors were considered for analysis of the occurrence of damages and pattern of damages. The observation and discussion above gave some idea about the damages and influencing factors of the tunnel damage. There were many slight damages and very little severe damages. The reason for this can be attributed to some factors such as, the size of tunnel being small, the tunnel being a deep tunnel as shallow tunnels get affected more comparatively, the tunnel being far from the epicentre, the quality of rock being pretty good.

Even though the epicentre was far from the tunnel, the damages occurred because the depth of epicentre was very low. There were few unusual results as in the damage distribution for overburden depth and also for different rock types. The reason may be the occurrence of many considerable aftershocks and epicenter being very near, so the damages may have been accumulated after each shock. Also the distribution of rock types have influenced the damages. So one influencing factor may have its effect on the results while

considering the other factor. There is scope for further detail analysis of the site taking into account the particular rock types in the site and their properties. So further numerical analysis can be done to observe the characteristics of the site parameters and seismic damages and hence it may help to understand the results obtained in this paper more clearly or it can be relatable. So numerical analysis is certainly considerable for the next research topic.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

- Asakura T, Sato Y (1998) Mountain tunnels damage in the 1995 Hyogoken-Nanbu earthquake. *Q Rep Rtri* 39:9–16
- Aydan O, and Ulusay R (2015) A quick report on the 2015 Gorkha (Nepal) earthquake and its geo-engineering aspects. *Iaeg*, 26 pp
- Barton N, Lien R, Lunde J (1974) Engineering classification of rock masses for the design of tunnel support. *Rock Mech* 6:189–236
- Bhattarai -Executive G, Lees D, Niaz A (2015) The melamchi water supply project
- Chen Z, Shi C, Li T, Yuan Y (2012) Damage characteristics and influence factors of mountain tunnels under strong earthquakes. *Nat Hazards* 61:387–401
- Dhital MR (2015) Geology of the Nepal Himalaya Regional perspective of the classic collided Orogen. Springer, Berlin
- Dowding CH, Rozan A (1978) Damage to rock tunnels from earthquake shaking. *J Geotech Eng Div* 104:175–191
- Edco (2001) East Drilling Company Ltd. .Melamchi Diversion Scheme, Geotechnical Investigation Report
- Goda K, Kiyota T, Pokhrel RM, Chiaro G, Katagiri T, Sharma K, Wilkinson S (2015) The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey. *Front Built Environ* 1:8
- Hashash YM, Hook JJ, Schmidt B, John I, Yao C (2001) Seismic design and analysis of underground structures. *Tunnel Underg Sp Technol* 16:247–293
- Huang T, Ho T, Chang C, Yao X, Chang Q, Lee H (1999) Quick investigation and assessment on tunnel structures after earthquake report for the public construction commission, Taipei, Taiwan And The Relevant Reinforced Methods
- Okamoto S, Tamura C (1972) Behaviour of subaqueous tunnels during earthquakes. *Earthq Eng Struct Dyn* 1:253–266

- Rajyaswori S, Li X, Luo Y, Kumar MA, Xu K (2020) The effect of overburden depth on the damage of underground structure during earthquake. *E&Es* 455:012067
- Sharma S, Judd WR (1991) Underground opening damage from earthquakes. *Eng Geol* 30:263–276
- Shen Y, Gao B, Yang X, Tao S (2014) Seismic damage mechanism and dynamic deformation characteristic analysis of mountain tunnel after wenchuan earthquake. *Eng Geol* 180:85–98
- Towhata I (2008) *Geotechnical earthquake engineering*. Springer Science & Business Media, Berlin
- Usgs Center For Engineering Motion Data (2015) *Cesmd-A Cooperative Effort*
- Wang Z, Zhang Z (2013) Seismic damage classification and risk assessment of mountain tunnels with a validation for the 2008 Wenchuan earthquake. *Soil Dyn Earthq Eng* 45:45–55
- Wang W, Wang T, Su J, Lin C, Seng C, Huang T (2001) Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi earthquake. *Tunnel Undergr Sp Technol* 16:133–150
- Wang Z, Gao B, Jiang Y, Yuan S (2009) Investigation and assessment on mountain tunnels and geotechnical damage after the Wenchuan earthquake. *Sci China Ser E Technol Sci* 52:546–558
- Yashiro K, Kojima Y, Shimizu M (2007) Historical earthquake damage to tunnels in Japan and case studies of railway tunnels in the 2004 Niigataken-Chuetsu earthquake. *Q Rep Rtri* 48:136–141
- Zhang X, Jiang Y, Sugimoto S (2018) Seismic damage assessment of mountain tunnel: a case study on the Tawarayama tunnel due to the 2016 Kumamoto earthquake. *Tunnel Undergr Sp Technol* 71:138–148

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