TECHNICAL UNIVERSITY OF CIVIL ENGINEERING OF BUCHAREST
PhD Studies Department

RESEARCH REPORT NO. 1

RESISTANCE OF UNDERGROUND AND BURIED HYDRO-TECHNICAL CONSTRUCTIONS IN CASE OF EARTHQUAKE

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Bucharest 2011

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1. General aspects

The biggest catastrophes recorded on the surface of our planet were caused by earthquakes. The concept of earthquake means a phenomenon of great complexity, characterized mainly by the disordered movement of the earth’s crust, caused by massive releases of energy that occur in the deep.

In general, seismic movements occur unexpectedly, and their intensity may vary from values that can be intercepted (only sensed by very sensitive devices) to severe shocks (with serious effects upon humans and disastrous consequences upon constructions.

The earthquake begins with a strong shock, similar to an explosion, located in an area inside the Earth, called the focus or hypocenter. The radial (vertical) projection of the focus on the Earth's surface is called epifocus or epicenter.

Energy developed within the focus is transmitted through elastic waves of various types, the intensity of which decreases with the distance of the hypocenter. Also associated with a given location, epicentral distance and focal distance can also be defined (fig.1.1.)

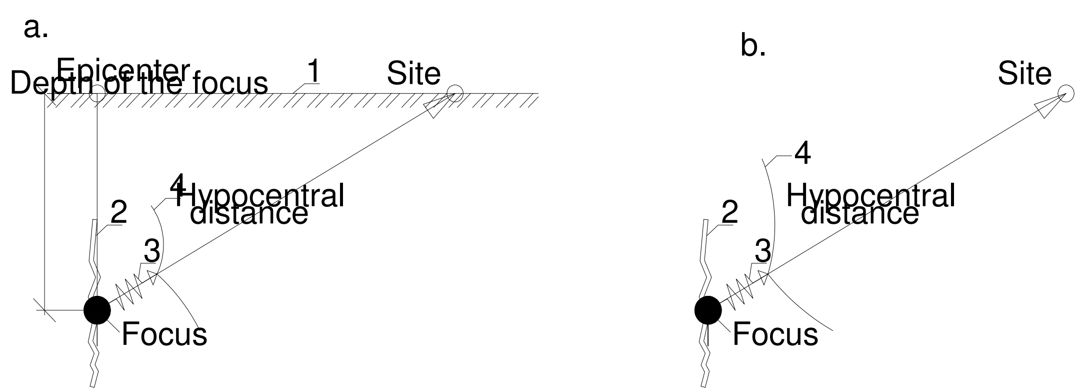


Fig.1.1. Diagram and notation for an earthquake:
a- vertical plan, b- horizontal plan,
1 – surface of the land, 2 tectonic fault, 3 - propagation direction, 4 - wave front.

Apart from the source of its occurrence, the earthquake itself is represented by the vibratory wave system that spreads through the earth, reaching the surface. There are two main types of deep-elastic waves whose speeds and energies are influenced by the physical state and geological composition of the rocks through which they pass, namely:

- Primary waves –are longitudinal waves propagating by changing the volume of the environment they pass by, producing compression-stretching deformations.
- Secondary waves - are cross-section waves with pulsation, with shear effects, perpendicular to the propagation direction.

2. Resistance of buried constructions in case of earthquake

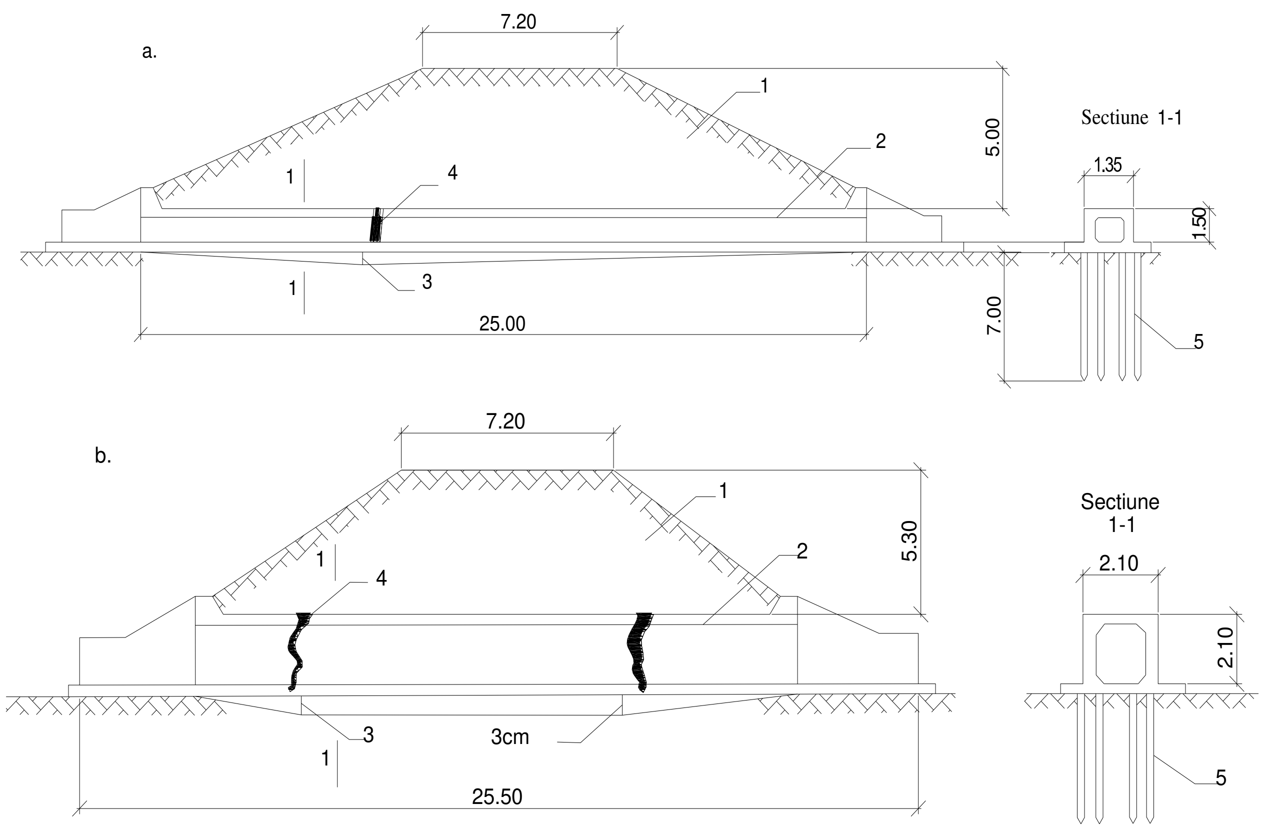
Resistance of constructions upon the Kanto earthquake (1923)

The Kanto earthquake (Japan, 1923) caused the degradation or destruction of about 70% of the drainage ducts on the banks of the rivers in the area. Some of these works are made of reinforced concrete pipes with a section from 0.45x0.45 m to 3.20x3.80 m and lengths from 13.50 m to 42.00 m. The pipes were laid on concrete bored piles or on wooden piles, which shows that the resistance of the foundation ground was poor.

In Figure 2.1. there are shown some types of damages found. Thus, uneven and high amplitude subsidence (1 to 24 cm) of pipelines were identified.

Due to the position of the piping lengths, a single crack in the middle (fig.2.1.a), two cracks approximately symmetrical to the middle (Fig.2.1.b), numerous cracks distributed generally uniformly along the length (Fig.2.1.c) occurred.

The simple concrete pipes surveyed had relatively small cross sections with a diameter of 0.45 and up to 0.60x0.60. Their length varied from 31.00 to 52.00 m, and the foundation was on wooden piles, reinforced concrete or concrete bored piles. The subsidence found was similar to that of reinforced concrete pipes; they caused relatively few cross-section cracks.



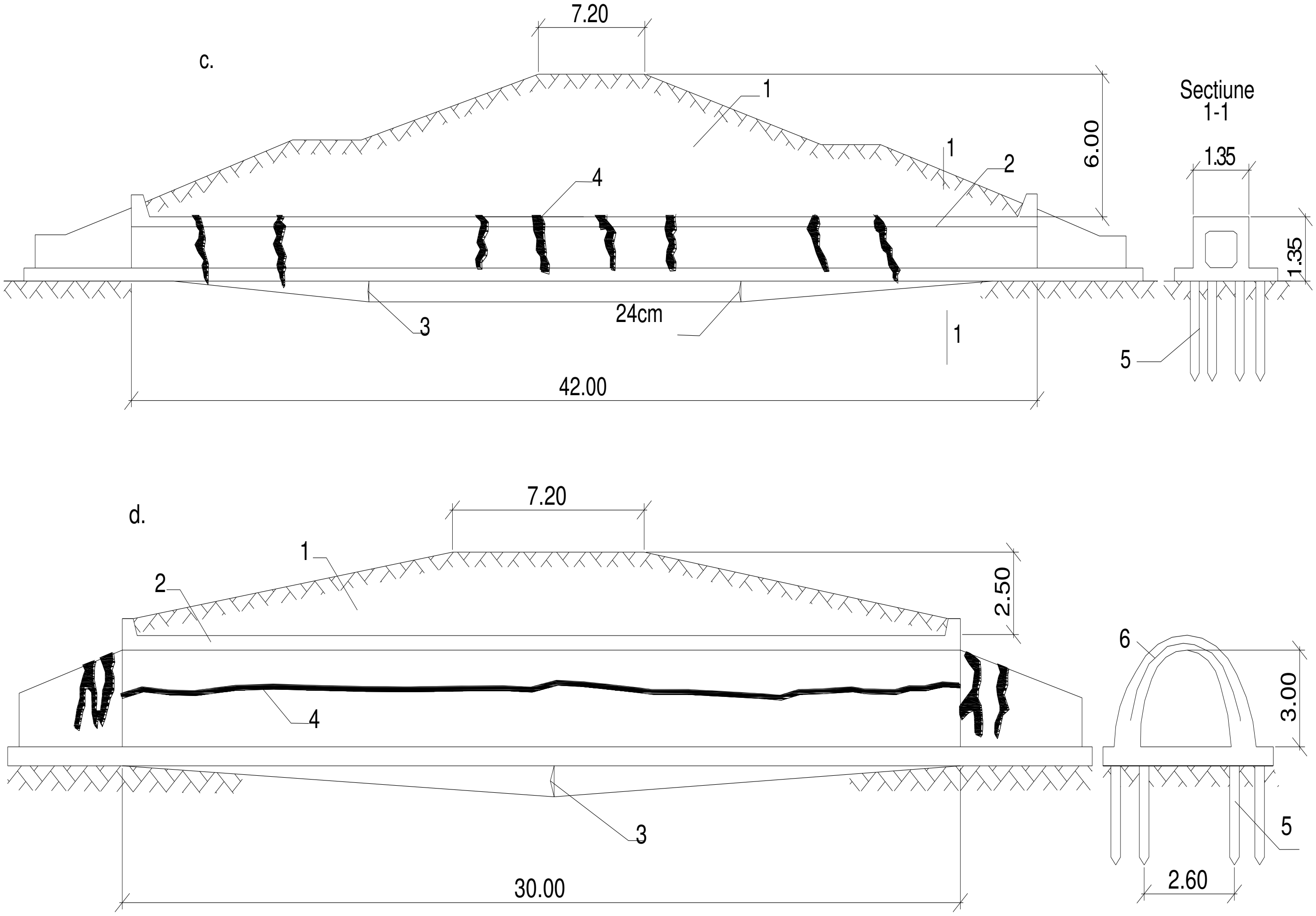


Fig.2.1.Damages caused by the Kanto earthquake at the drainage pipes of the river banks:
a-unique cross-section crack, b-two cross-section cracks, c- cross-section cracks uniformly distributed along the length, d-longitudinal crack, 1-pier, 2-drain line, 3-subsidence, 6-fitting.

In the reinforced concrete pipe (fig.2.1.d) a single longitudinal crack occurred along the length of the vault and sloping cracks in the lateral walls of the portal. Damage shows a high load from the additional horizontal overpressure pressure in the transverse direction of the pipeline.

The earthquake Resistance statistics of the buried pipes showed that, in general, the number of damage to these works is lower than in the case of on-surface constructions.

Resistance of constructions upon the San Francisco earthquake (1906)

During the San Francisco earthquake (1906), most damage to the water supply pipes occurred in the crossing areas of fillings. In strong, healthy land, the defects were minimal.

Resistance of constructions upon the Long Beach earthquake (1933)

During the Long Beach earthquake (1933), 52% of the water supply pipe damage occurred in the filling areas, and 38% in the areas with muddy land and high groundwater levels. Also on this occasion it was found that 33% of all damages, in the form of cross-section cracks, occurred in the networks on the three streets coincided with the direction of the main seismic waves.

Resistance of constructions upon the Tashkent earthquake (1966)

During the earthquake in Tashkent (1966), the underground pipeline network of the city suffered serious damage and destruction. Between April 26, 1966 and March 24, 1967, 198 rupture of joints of cast iron pipes, 108 damages of ceramic sewer pipes and other damages of reinforced concrete and asbestos pipes were recorded. There were no seismic damages in the steel pipes. The location of the earthquake in Tashkent under the city center, and in particular the repetition of seismic activities, determined its effects on the constructions under consideration. The main forms of destruction were the breaking of the joints between the cast iron pipes and the breaking of the ceramic sewer pipes. Deformations and breaking of joints under the action of seismic forces were due to uneven displacements of the pipelines and the surrounding environment, accompanied by the expulsion and detachment of the joint strength material.

Concrete reinforced pipes suffered less damage. At a collector made of reinforced concrete tubes with a diameter of 1200 ...1400 mm, cracks were found at joints made as concrete belts. The cracks developed throughout the perimeter at the inner side of the joints. At the flexible joints of reinforced concrete pipes no damage was found. Insignificant open cracks were observed in the annular direction to large diameter reinforced concrete tubes (D> 1000 mm). These cracks did not affect the continued normal operation of the feeds.

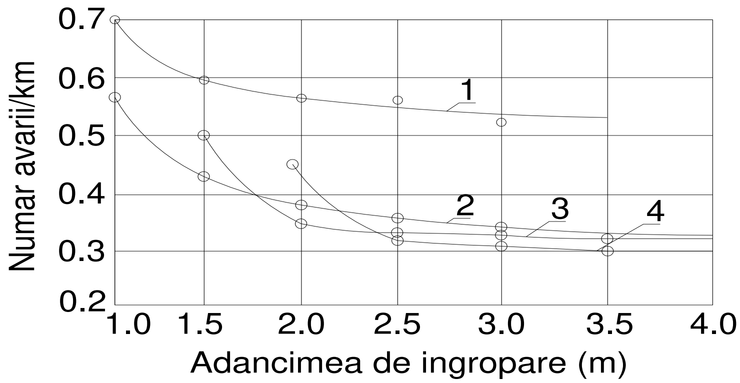


Fig.2.2. Variation of damage / km with depth
burial of cast iron tubes with diameters:
1-100200 mm, 2 - 200 ...400 mm, 3 - 400 ...600 mm, 4 - 600 ...< 800 mm

Another issue analyzed during the Tashkent earthquake was that of the depth of pipe laying on their earthquake resistance. Figure 2.2. shows that in the case of cast iron pipes the number of damages depends on the number of burial depths. It is noted that the number of damages per linear meter decreases proportionally with the increase in burial depth.

3. Resistance of underground constructions in case of earthquake

Underground work is usually considered less vulnerable to seismic actions.

Because underground works are generally surrounded by stable land, moving them into during seismic activity tend to be minimized, making them less sensitive to seismic damage than other structures such as bridges or foundations (fig.3.1.

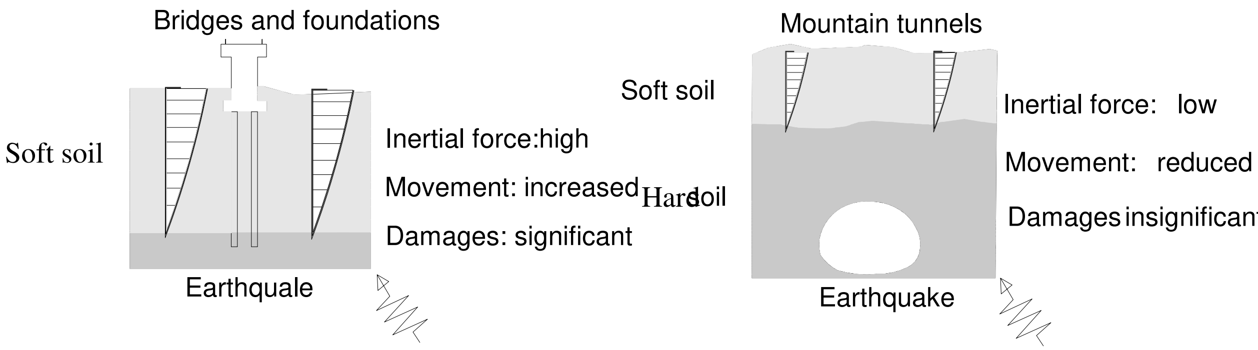


Fig.3.1. Differences in terms of resistance during an earthquake between bridges, foundations and mountain tunnels.

In Japan, four major earthquakes were felt by the underground works: the Kanto earthquake (1923), the Izu-Oshima-Kinkai earthquake (1978), the Hyogoken-Nanbu earthquake (1995) and the Niigataken-Chuetsu earthquake 2004. The damage caused by these earthquakes is shown in table 1. and in Fig. 3.2. a sketch with the area affected by the four earthquakes is shown.

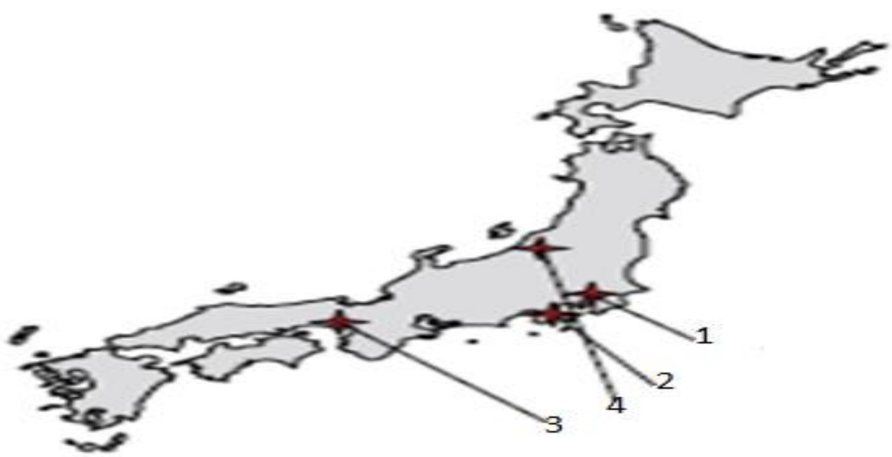


Fig. 3.2. Areas affected by the four earthquakes.
1,2,3,4- corresponds to item no. from table 1.

Table.1

No.	Earthquake	Magnitude	Earthquake intensity	Consequences
1	Kanto 963.	7.9	6	Damage to 82 tunnels. 25 tunnels require reconstruction.
2	Izu-Oshima-Kink 1978	7.0	5	Damage to 9 tunnels. 2 tunnels require reconstruction.
3	Hyogoken-Nanbu 1995	7.2	7	Damage to 7 tunnels. 5 tunnels require reconstruction.
4	Niigataken-Chuetsu 2004	6.8	7	Damage to 24 tunnels. 5 tunnels require reconstruction.

The Resistance of constructions upon the Kanto Earthquake (1923)

The Kanto earthquake has had catastrophic consequences, being particularly strong and taking place in densely populated and heavily industrialized territory. It caused many damages, they were classified according to the following criteria:

- cracks - defects formed in the breakdown process, which do not comprise the entire cross section of the tunnel;
- local breaks - isolated point movements of the structure;
- collapsing - the destruction of the vault supports in a large area of the tunnel, followed by the filling of its section with the ground broken;
- transformations in the structure - alteration of the cross-sectional shape and displacement of the axis.

Constructively, most of the railway tunnels in the Tokyo area were on the single or double way, with masonry or concrete lining, with thicknesses varying between 25 and 60 cm. They were on the mountain slopes, crossing alluvial fields, compact clays, cemented layers of bushes and volcanic lakes, fine aquifer sand layers.

Fig. 3.3. shows the Namuya single-track tunnel, 745 m long, built 5 years before the earthquake. It crosses an area of hills lying along the seashore, the middle sections of the trail undercrossing water courses. The rocks in the area of the route are tertiary-tufted formations, tophus shrubs and sandstones.

The cross section of the horseshoe-shaped tunnel (Fig.3.4.a) indicates the existence of large vertical, vertical and horizontal lithostatic pressures in the area. The tunnel vault was made of brick masonry, and the concrete walls in areas with tophus rocks and brick in the rest. Following the earthquake, the initial axis of the tunnel changed to an important length, with maximum displacements reaching 55 cm vertically and 45 cm laterally. These occurred at about 350 m from one of the portals (fig.3.4). They are explained by the phenomena of massive sliding (the sliding of the rocks soaked with water on the slopes).

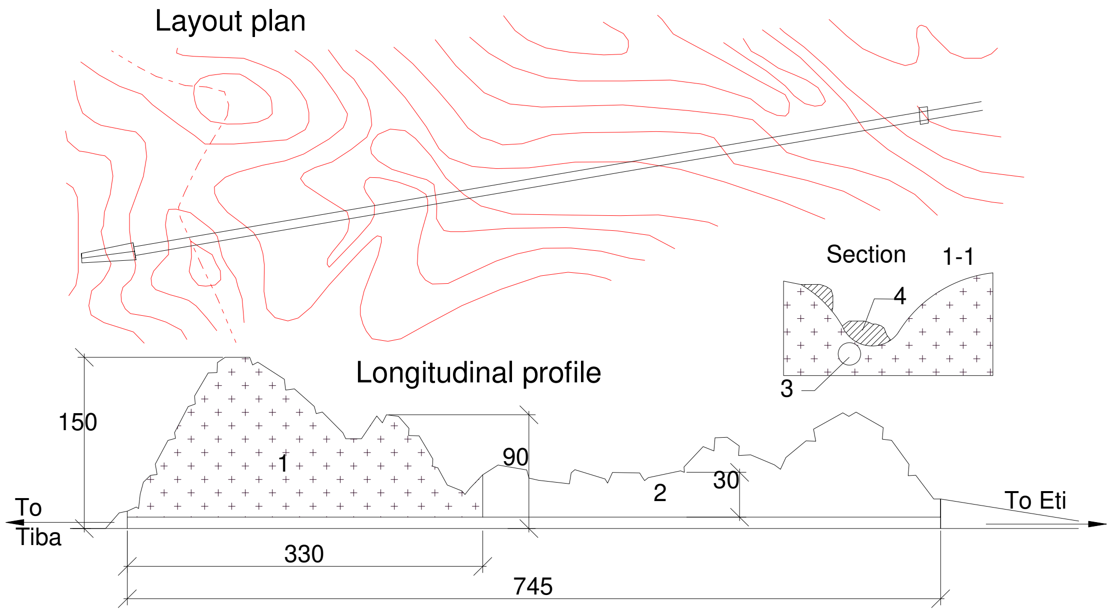


Fig.3.3.Namuya tunnel damaged by the Kanto earthquake:
1-tophus, 2-tophus rocks, 3-tunnel, 4-aquifer fields.

Not so easy to explain are the horizontal displacements of the tunnel excavation, 5-8 cm to the mountainside, in the area 200-300 m from the left portal (Fig.3.4).

Cross-section cracks have formed in the vicinity of the portals. Larger degradations, in the form of cracks and faults, wall collapses, vault collapses with rock penetration into the tunnel, have occurred especially in areas with tophus rocks and lower tunnel depths (Fig.3.5)

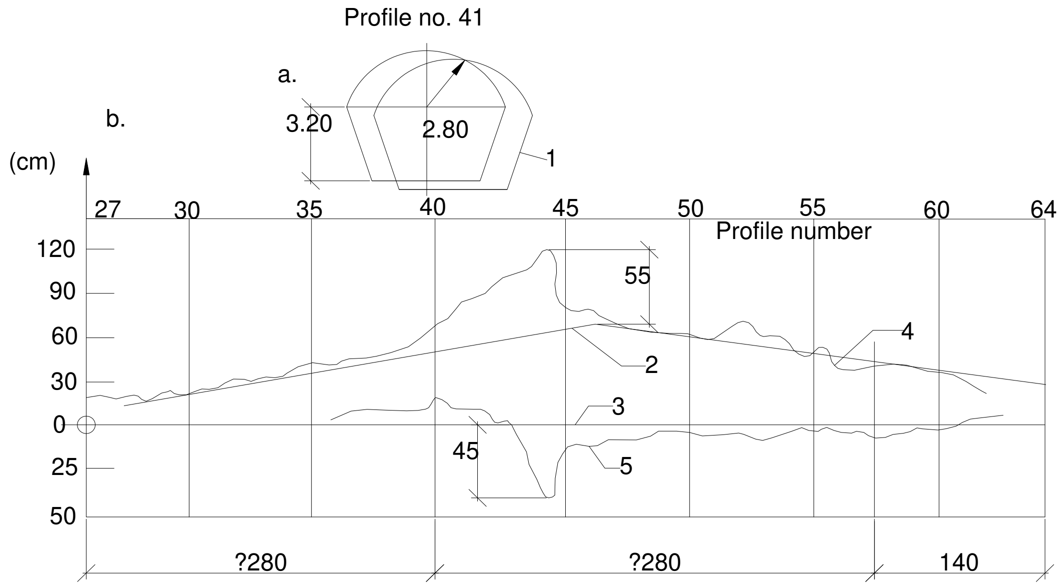


Fig.3.4.Namuya tunnel damaged by the Kanto earthquake:
a-cross-section, b-longitudinal profile displacements,
1-shifts after earthquake, 2-original profile, 3- initial axis
4-vertical displacements in axis, 5-horizontal displacements in axis.

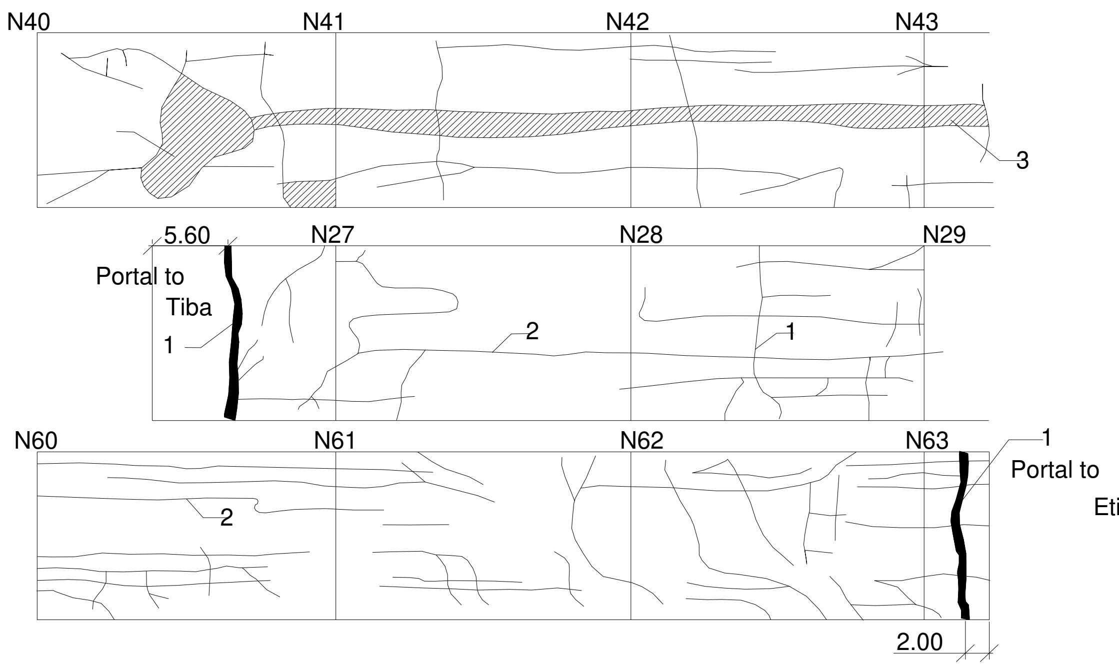


Fig.3.5.Namuya tunnel - Kanto earthquake cracks and crashes:
1-cross-section cracks, 2-longitudinal cracks, 3-vault collapses.

Hakone tunnels no.3 and no.7 (Fig.3.6.a, b) with double ovoid sections are located on the slopes.

The earthquake caused numerous cross-section cracks and faults in the portal area, on sections up to 60 m (fig.3.6.c, d, e).

The structure has moved outward in many places, and on a 16.5 m sector it has moved upwards. It has been found that the damage decreases as the depth of the tunnel increases.

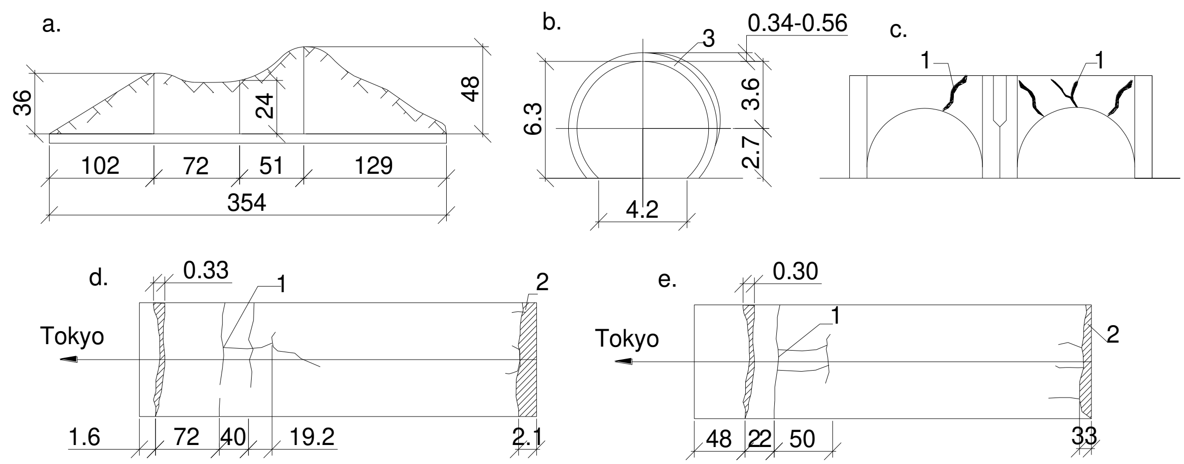


Fig.3.6. Hakone tunnels - Kanto earthquake damage:
a-long profile, b-type cross-section, c-damage to portals, d-damages to the vault
1-faults, cracks, 2- vault crash, 3- remnant movement.

Another example, which highlights the influence of the structural composition and the type of lining on the seismic Resistance, is the Komine tunnel (fig.3.7 This double-track railway tunnel is in the final construction phase at the time of the Kanto earthquake.

The tunnel crosses a red clay field. Depending on the depth of the tunnel, both the material and the liner type vary. The left sector of the tunnel (55 m from the portal) was executed in open trenches with reinforced concrete support walls, covered with prefabricated tiles. At the time of the earthquake the support walls, partially covered with tiles, and the monolithic reinforced concrete portals were made. Construction of the other part of the tunnel differs depending on the depth: reinforced concrete vault with concrete walls, brick or stone masonry (fig.3.7

As a result of the earthquake, both supporting walls moved inward, and a wide crack appeared on the face of the left portal. In the areas where the tiles were not installed, large rotation of the supporting walls was found (Fig.3.7)

The most important damages in the covered area of the tunnel occurred in the reinforced concrete section, located at a small depth (fig.3.7.c) and not in the masonry structure, located at a greater depth, where a single larger crack appeared at a distance of 7 m from the right portal.

There have been numerous cracks in the structure, with depths of up to 10 cm. This leads to the conclusion that the low depth of the tunnel and the large declivity of the mass above it negatively influences the stability of the tunnel at seismic loads.

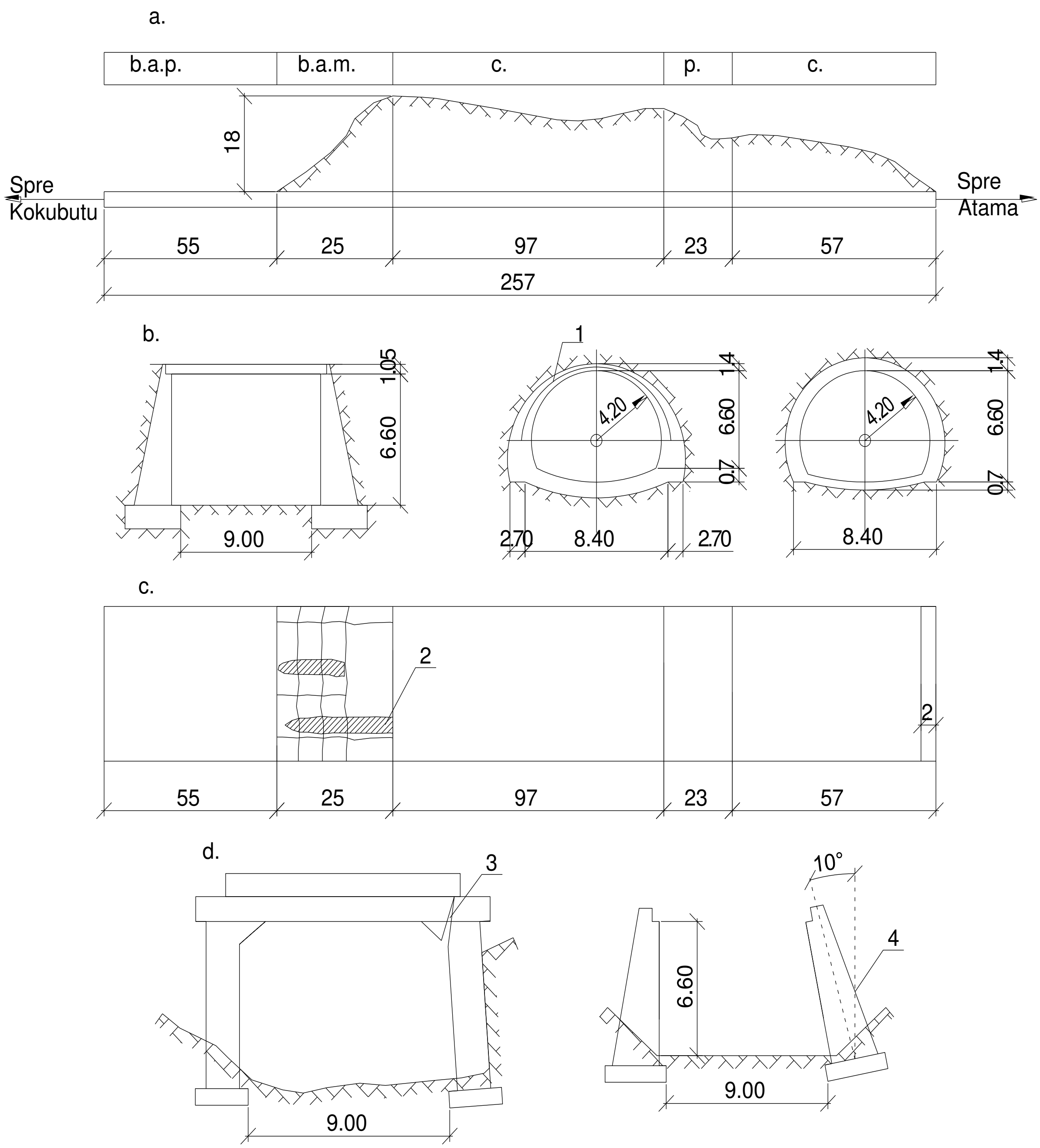


Fig.3.7. The Komine tunnel - the Kanto earthquake:
a-long profile, b-cross-section type, c-damage to the vault and walls, d-damage in the area with lining of prefab concrete; 1-reinforcement, 2-cracks and holes in the vault, 3-cracks, 4-rotating supporting wall; prefab reinforced concrete b.a.m.-concrete, monolithic reinforced bam-concrete, c-brick, d-stone.

In Figure 3.8. it is shown the longitudinal profile and the plane of a railway tunnel, made in volcanic ash rock, with inclusions of solidified pieces of lava.

Following the Kanto earthquake there occurred:

- stone wall collapses and stone masonry abutments that strengthen the inner wall in the left portal area.
- Cross-section cracks in the left wall in the left portal area.
- the collapse of the stone masonry vault in the right portal area.

These damages are believed to have occurred due to slipping phenomena from the slope. Significant damage has occurred in 11 tunnels on the Atamy line. They have a horseshoe-shaped lining for double track and were built on the slopes. The lining is made up of 60-...100 cm thick stone.

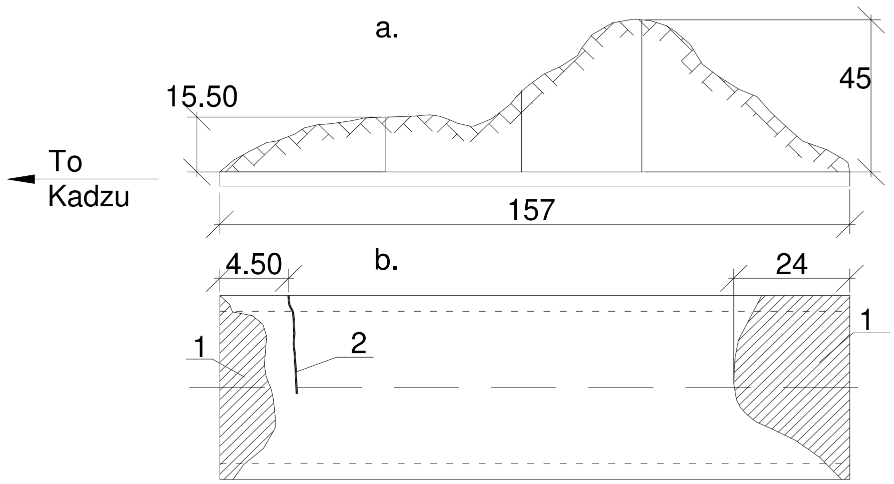


Fig.3.8. The destruction of the portico of a railway tunnel at the Kanto earthquake:
a-profile in the long, b-damage to the vault, 1-crashes, 2-cracks.

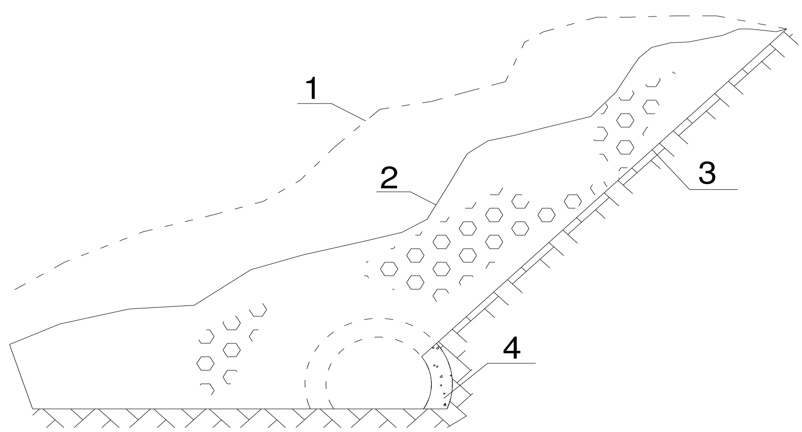


Fig.3.9. Destruction of a coastal tunnel upon the Kanto earthquake:
1- land line before earthquake, 2-slope collapse,
3-line restoration of the slope after the earthquake, 4- remaining part of the lining.

During the earthquake, the tunnel parts in the vicinity of some portals were destroyed by the collapse of the slopes in lengths of tens of meters. On the rest of the length of the tunnels, in the sections between the vault and walls, numerous cracks have formed.

The route was restored in the area by a suitable slope (Fig.3.9)

Types of seismic damage are also illustrated in Figure 3.10 showing the damage caused by the Kanto earthquake to a railway tunnel with a stone masonry lining on the Kodzu line. Main breaks consist of:

- vault collapses,
- cross-section and longitudinal cracks, especially in the vicinity of the portals,
- residual deformations in cross-section.

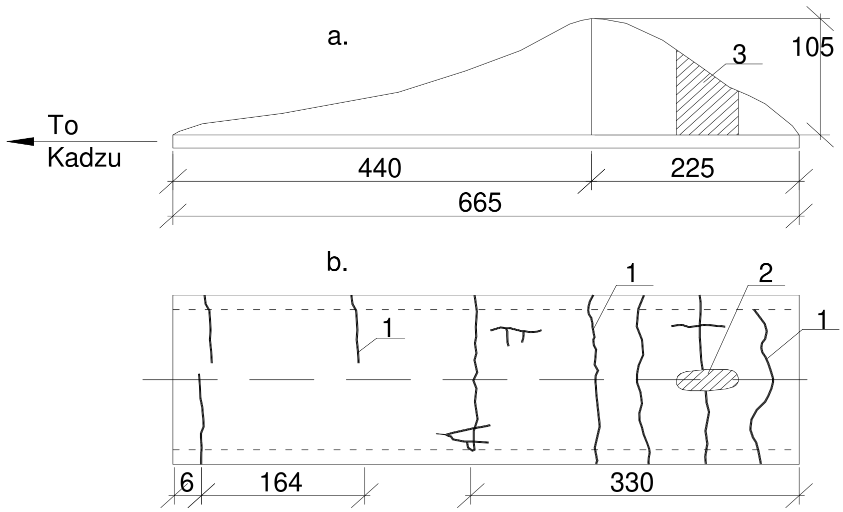


Fig.3.10. Kodzu tunnel - damage upon Kanto earthquake:
a-longitudinal profile, b-damage to the vault and walls, 1-cracks,
2-vault collapses, 3-fallen area.

Resistance of constructions upon the Niigataken-Chuetsu earthquake (2004)

On October 23, 2004, an earthquake of 6.8 in magnitude occurred in Japan at 37^{o}17' N latitude and 138^{o}52' E longitude, at a depth of 13 km.

The earthquake caused the derailment of a train on a line in the Shinkansen system, and several mountain tunnels suffered serious damage. Twenty-four tunnels have been damaged and five of them (Uonuma, Myoken, Wanasu, Tenno and Shin-Enokitoge) require consolidation.

Figure 3.11 shows the distribution of severely damaged tunnels during the earthquake, and Figure 3.12 shows the number of damaged tunnels.

Fig.3.11. Distribution of severely damaged tunnels
upon the Niigataken-Chuetsu earthquake.

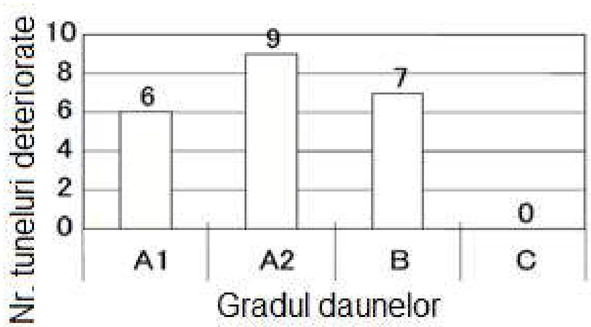


Fig.3.12 Number of damaged tunnels and degree of damage.
A1-major damage requiring repairs and consolidations, A2 damage requiring repairs,
B-damage that does not require repair, C-no damage.

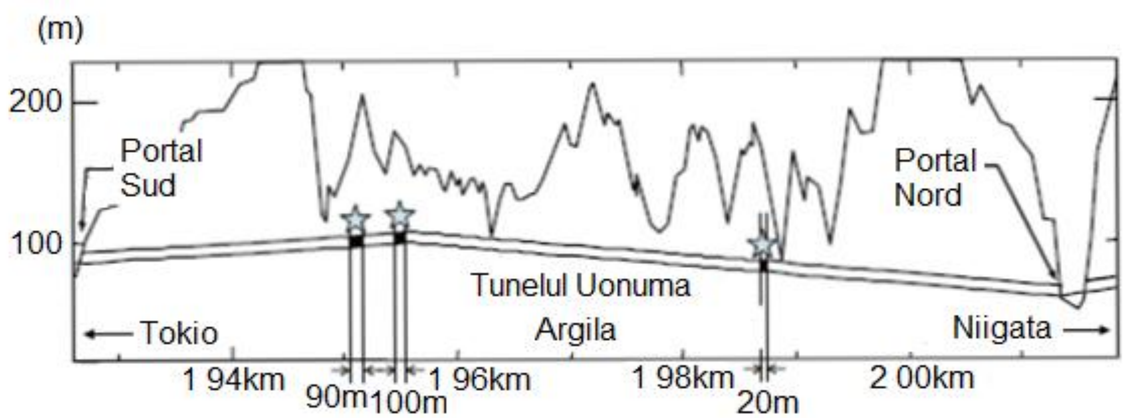


Fig.3.13 Synoptic Profile of Uonuma Tunnel,
with emphasis on the three sections in which it suffered serious damage.

Figure 3.14 shows the most severely affected section, there was damage to the concrete coating that fell apart and fell on the track. The largest block of detached concrete was about 2 m^3 weighing about 5 tons. Other damage was observed at a narrowing of the section of the tunnel.

The tunnel was in a critical state, it was closed for two months for repairs, it was necessary to break and remove degraded concrete being replaced by prefabricated reinforced tiles, tunnel repairs are shown in figure 3.15.

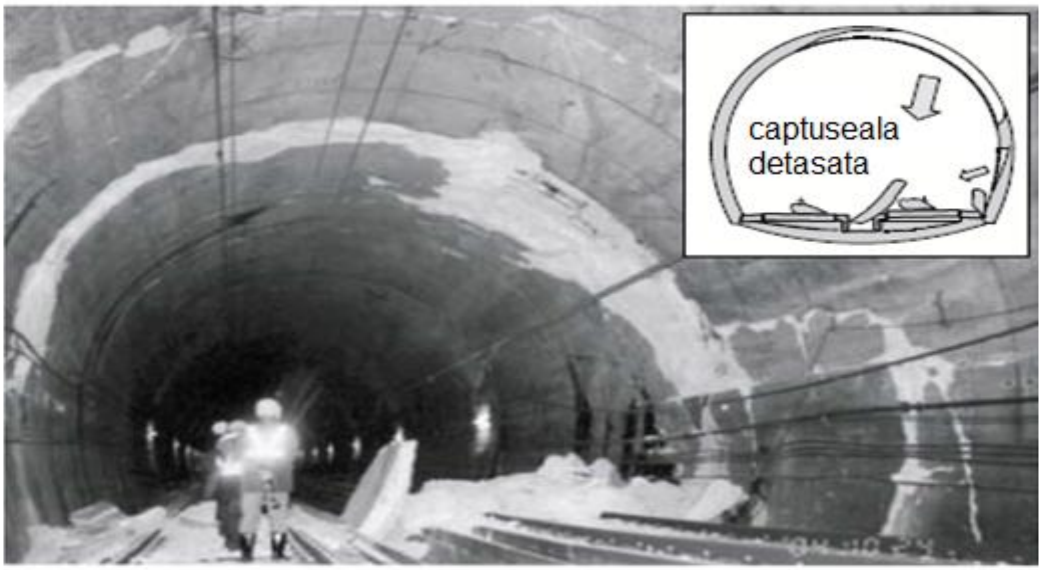


Fig.3.14 Damage to the Uonuma tunnel.

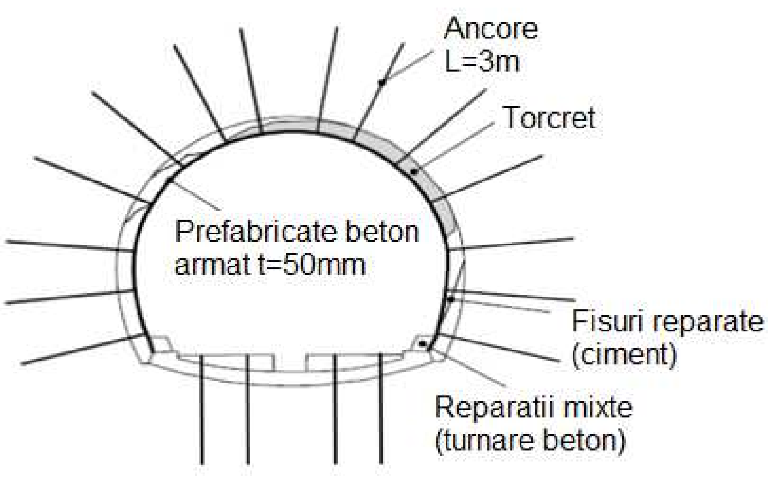


Fig.3.15 Repairs to the Uonuma tunnel

Damage also occurred at the Myoken tunnel, which suffered longitudinal cracks on a distance of about 50 m (Fig.3.16) and some exfoliations of the coating.

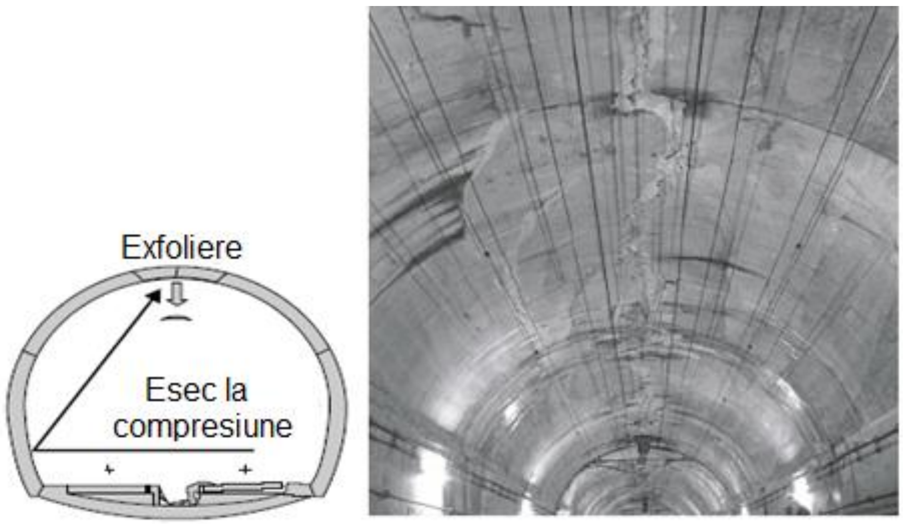


Fig.3.16 Damage to the Myoken tunnel

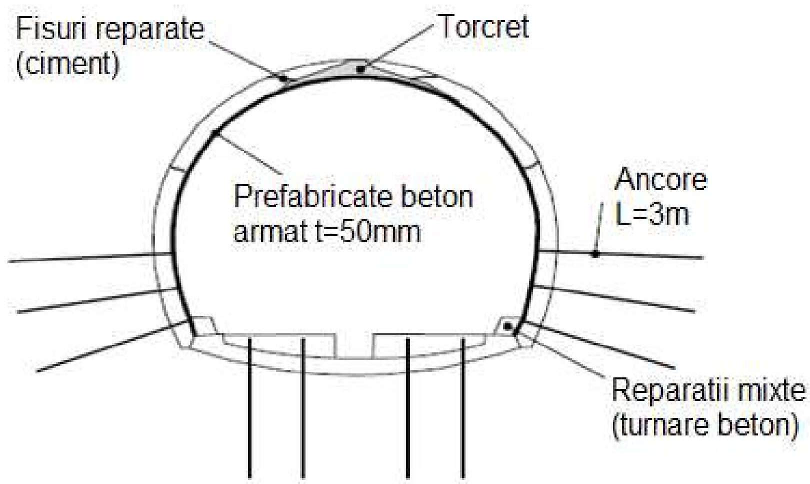


Fig.3.17 Repairs to the Myoken tunnel

The Wanatsu tunnel suffered due to seismic actions, with about 40 m long longitudinal cracks and large blocks of concrete detached from the coating (Fig.3.18).

Fig.3.18 Damage to the Wanatsu tunnel

Resistance of constructions upon the San Francisco earthquake (1906)

During the earthquake in San Francisco, April 18, 1906, a hydrotechnical gallery and a railway tunnel were damaged. The drainage gallery of the San Andreas dam, located in strong rocks of diabase and serpentinite, was sheared as a result of a tectonic slide.

The gallery part located west of the sloping plane underwent a 2.40 m displacement. In the portal area, the gallery, lined with stone masonry, was destroyed on a length of 8.50 m.

A 1890-meter-long railway tunnel in the Santa-Cruz mountains, in the marginal area of the San Andreas fault, has undergone sliding displacements. The shear line intersected the tunnel route at an angle of 80 ° at a distance of 120 m from the northeast portal and the horizontal displacement had an amplitude of 1.50 m. The tunnel axis deviation from the initial position gradually decreased in relation to the distance from the place of rupture, becoming ignorable at a distance of 1500 m.

Resistance of constructions upon the Dagestan earthquake (1970)

The earthquake in Daghestan- the Union of Soviet Socialist Republics (May 15, 1970) had the VIIIth grade MM and was followed by other IV-V grade shocks in the coming days. In the area of the earthquake, several underground works (adduction and escape galleries, diversion and injection galleries, car tunnels) by AHE Cirkeisk on the Sulac River were under construction.

The constructive composition of tunnel sections and escape galleries is shown in Figure 3.19. They are lined with plain or reinforced monolithic concrete. The car tunnel, which passes through an area with large tectonic abnormalities, was used during the construction of metallic reinforcement. At the time of the earthquake, the Sulac River was deflected through the diversion gallery. On the permanent discharge base construction, the foundation frame and the lower part of the channel walls were concreted. The vault was reinforced with metal anchors and welded mesh. The anchors were 2.00 m long, with the fault type. Overall, about 15 km of galleries and tunnels had already been built.

The earthquake has caused more damage to underground work. The total volume of crashes at these works was about 4000 m^3.

Important damages occurred in the crossing area of the fault by the car tunnel (Fig.3.20

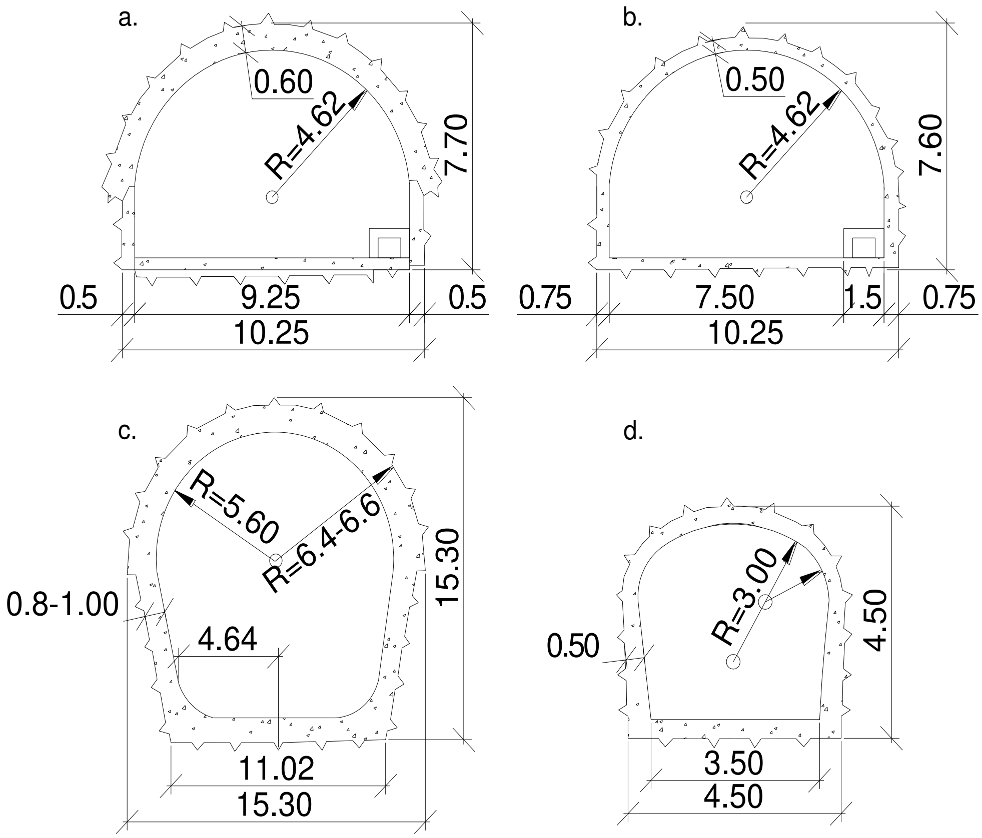


Fig.3.19.Types of UHCirkeisk lined sections:
a-tunnel car in rocks with a coefficient of strength f = 1-2, b-car tunnel in rocks with f = 4-7,
c-gallery run, d-gallery drainage and injections.

In the rock massive there appeared cracks with openings from 0.5 to 1.0 m. Directions of these cracks formed sharp angles or 90° with the tunnel axis. The rocks in the area are different, from poorly to strongly cracked, predominantly poorly cracked rocks.

In the other areas of the underground works there were various degrees of damage, consisting of:

- cracks,

- displacements of the structure
- rock collapses to volumes of several tens of meters[3].

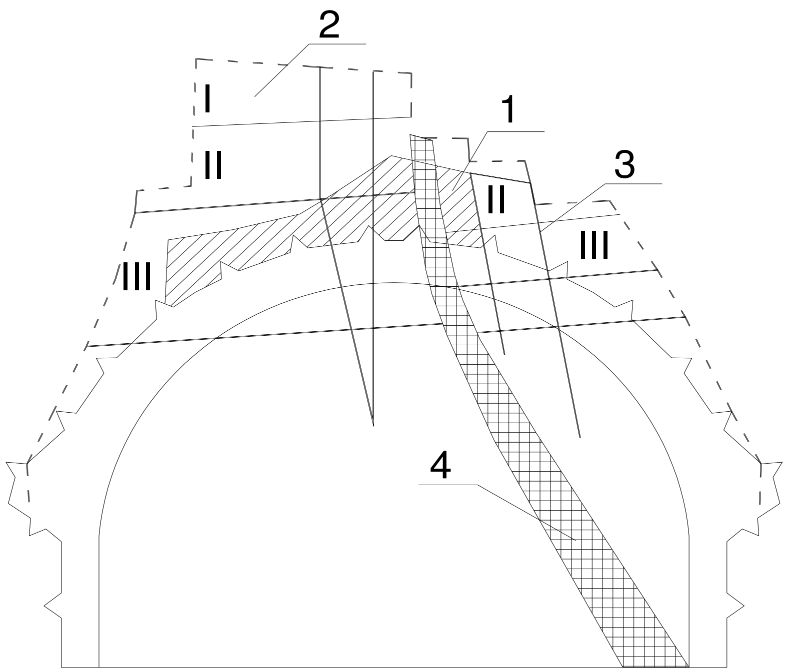


Fig.3.20 The collapse of the vault at the UH Cirkeisk tunnel:
1-collapse after the opening of the excavation, 2-collapse after the earthquake,
3-open cracks, 4-tectonic fault, I, II, III-clay layers.

The most significant rock collapse, with a volume of approx.30 m^3, occurred, with the anchors and the reinforcement mesh, from the escape galley vault. Throughout its route there have been identified exfoliations of small pieces of rock or fillings from tectonic cracks, rock drops from the walls and excavation vault, cracks in the hearth and the walls of reinforced concrete lining with openings up to 10 mm. Some crashes can be explained by fragmenting the rock into blocks separated by normal tectonic cracks or along the plane of schist (fig.3.21).

It has been found that anchor support has yielded to several areas. It results that the anchors did not sufficiently support the rock packages above the gallery, avoiding the relative displacements between the layers. Anchor supports are considered to be applicable only to temporary works.

Interesting data were obtained by analyzing the Resistance upon earthquake of the 795m long tunnel. The tunnel coating is made of reinforced concrete, with some additional support areas with metallic grooves; Portals are reinforced concrete. After the earthquake, significant slopes were identified at both portals. It is noted that during the excavation of the tunnel, there have been significant rock falls that have been stabilized by wedging.

In the tunnel areas in the vicinity of the portals there have been numerous ring-shaped cracks and detachments, especially in addition to shrinkage joints. The crack depth was 30 ...40 cm and their opening was maximum 5 mm.

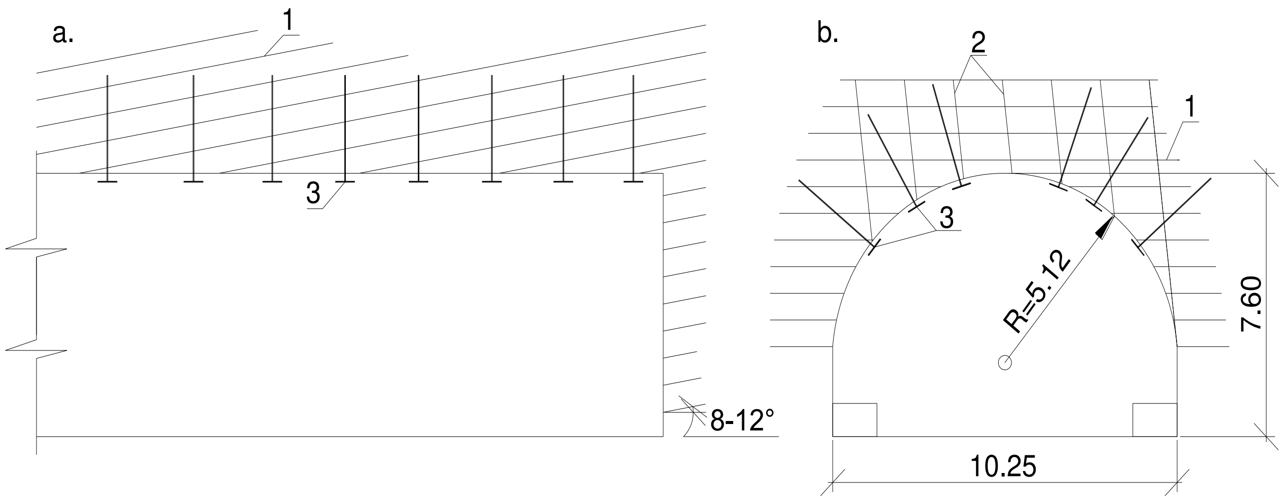


Fig.3.21). Anchoring of tunnels and galleries excavations at U.H.Cirskeik:
a-long section, b-cross-section,
1-direction of schist plans, 2-tectonic faults, 3-anchors.

In an area of the tunnel, located at approx. 300 m of exit, there occurred faults with openings up to 12 mm, between the walls and the basin at the base of the tunnel (fig.3.19.a), and in the vault a zigzag fault system with openings up to 5 mm. There were no tectonic cracks in this area, but there was a stratigraphic boundary of some rocks with a coefficient of strength (according to Protodiakonov) from 4 to 7. It is believed that an essential role in the formation of longitudinal cracks at the wall-to-tack contact had the foundation's inhomogeneity and the local discontinuity of the structure.

In the tunnel areas with temporary supports, cracks and tectonic faults with openings from 1 to 20 mm were identified in the rock.

4. Summary of earthquake damage to buried and underground constructions

Classification of the types of damage

Figures 4.1.4.2 show the classification of damage types after the following earthquakes: Izu-Oshima-Kinkai (1978), Hyogoken-Nanbu (1995) and Niigataken-Chuetsu (2004).

Damages have been classified into three types:

- Type 1 - damage to shallow-depth tunnels (fig.4.3)

They are likely to be affected by earthquakes as they are often built into loose lands, where the seismic action is amplified by the large deformation of the land. In these tunnels there are often cracks in the vault due to the bending moments.

- Type 2 - Damage to tunnels due to poor geological conditions (Fig. 4.4)

This type of damage is visible in tunnels built in soft land, such as fractured areas, sometimes in tunnels with great land coverage. In fractured areas, the soil is soft and has a great displacement during the earthquake, and it also acts as a charge upon the coating.

- Type 3 - Damages that occur when an earthquake crosses a tunnel (fig. 4.5)

This type of cracks often appear due to shearing and cracks in round slices.

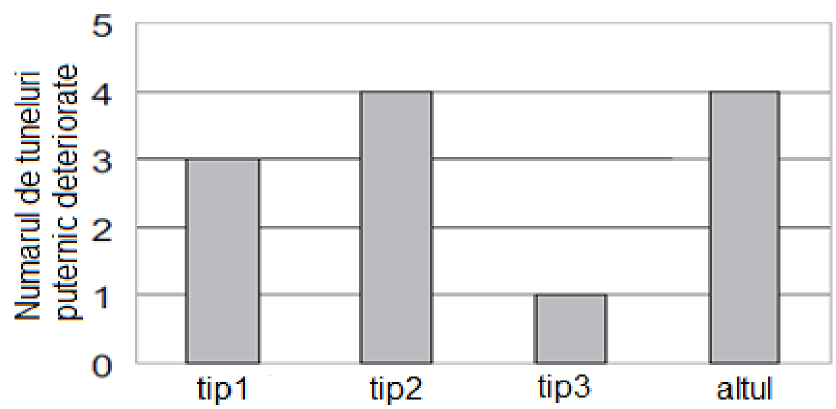


Fig.4.1 Number of damaged tunnels by type of damage.

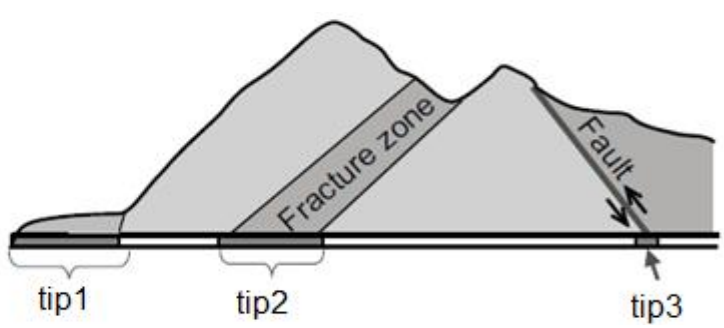


Fig. Classification of the types of damage

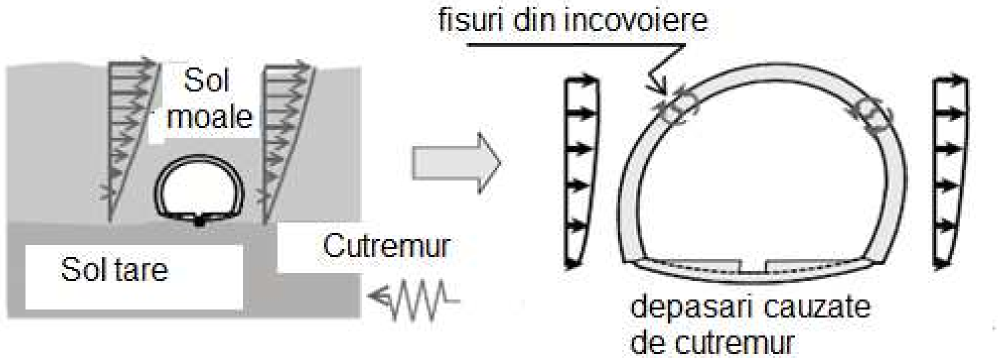


Fig.4.3 Type 1- shallow-depth tunnels

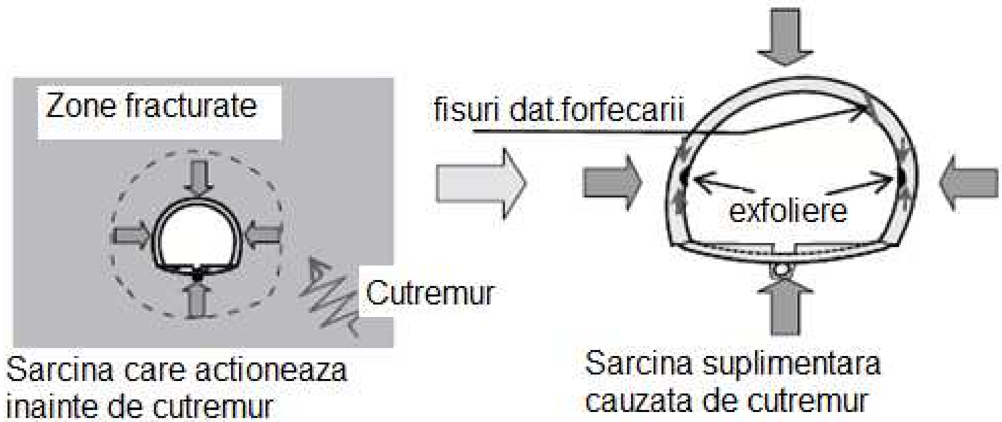


Fig.4.4 Type 2 - Tunnels built under precarious geological conditions

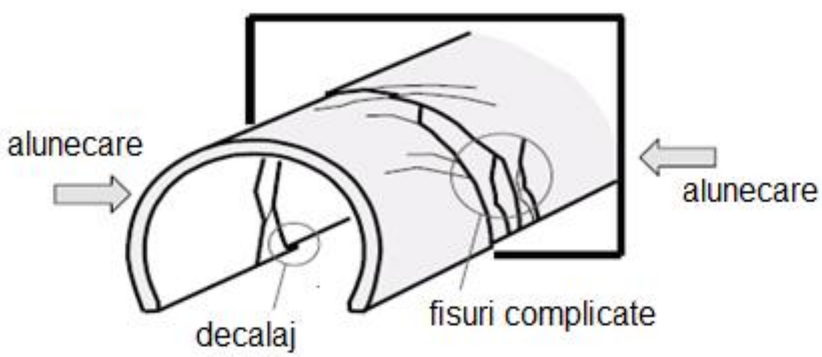


Fig.4.5 Type 3 - Damage caused by earthquakes acting across the tunnel

Conditions of the damage

The conditions under which tunnels are susceptible to damage are:

- Earthquakes of great magnitude
- The location of the tunnel towards the epicenter

Fig.4.6 shows the relationship between the magnitude of the earthquake (the most important earthquakes experienced in Japan), the distance to the epicenter and the number of severely damaged tunnels, it is shown that the risk of damage due to an earthquake is quite high in both cases.

The tunnels suffered considerable damage in areas where the distance to the epicenter was about 10 km, and in areas where the distance was between 10 and 30 km, considerable damage only occurred to earthquakes of a very high magnitude.

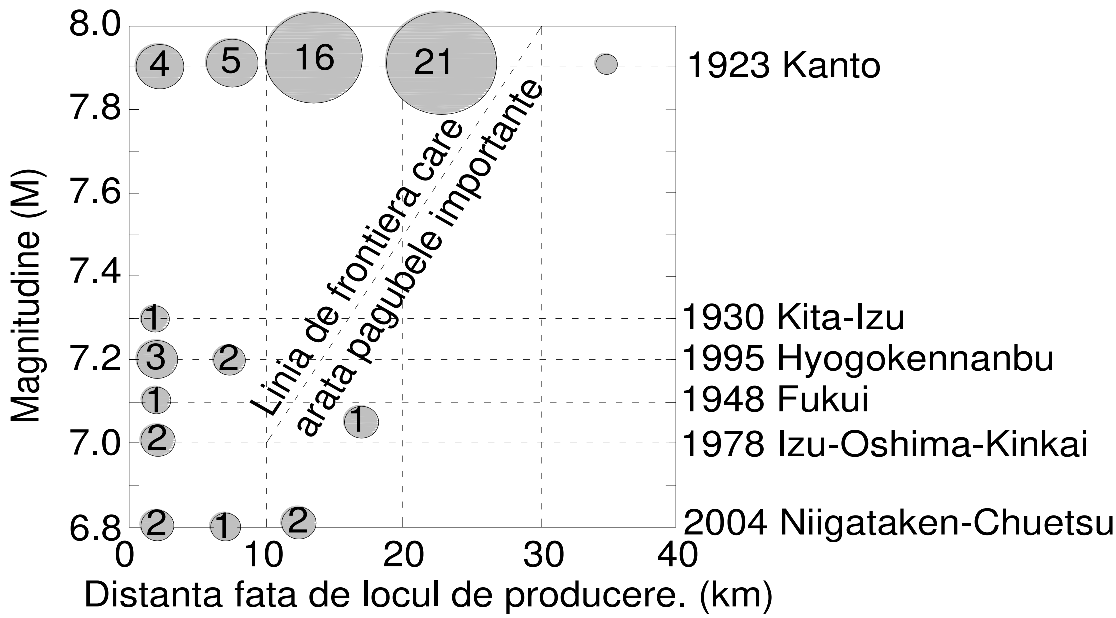


Fig.4.6. Relationship between the magnitude of the earthquake, the distance from the epicenter and the number of severely damaged tunnels.

Figure 4.7. is a synthesis of earthquake-induced problems in tunnels. The number of events related to seven different situations is illustrated herein. It is noteworthy that the main problems were caused by the instability of the massive slope above the portal.

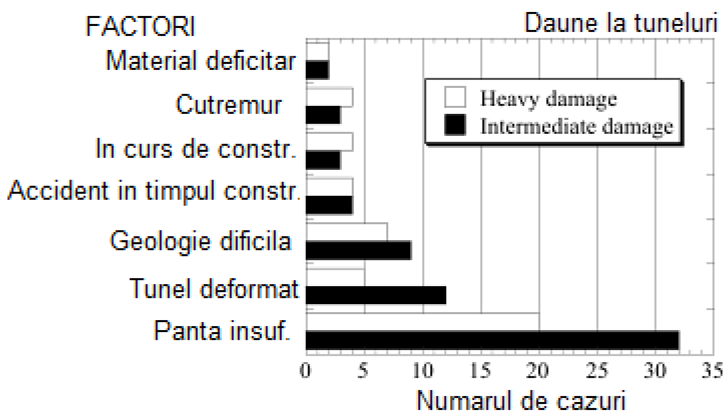


Fig.4.7 Factors related to seismic damage to tunnels

One of the frequent problems caused by earthquakes in tunnels is the insufficiency of the slope above the portal (fig. 4.8). It is important to consolidate the slope or build a protective structure.

Fig.4.8. The portal of the Haguro tunnel

Fig.4.9. Exfoliations of the coating in the Haguro tunnel

Fig.4.10. Extended longitudinal cracks in the Haguro tunnel.

Fig.4.11. Land sliding near the western entrance of the Haguro tunnel.

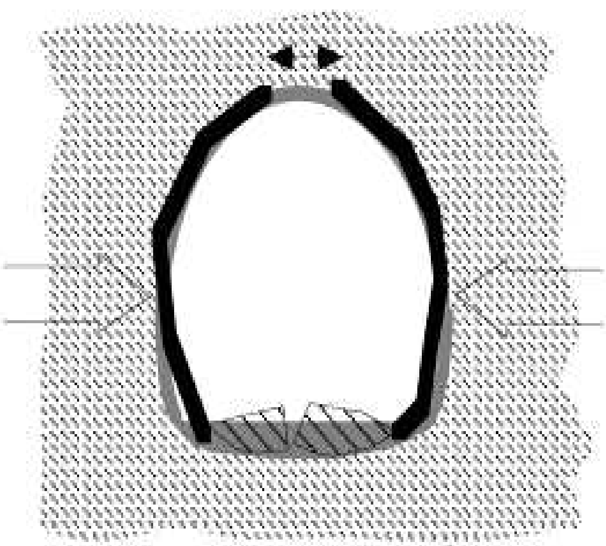


Fig.4.12. Diagram of the mechanism of deformation in the Haguro tunnel.

5. Bibliography

Seismic Engineering of Hydrotechnical Constructions - R.Prişcu, A.Popovici, D. Stematiu, L. Ilie, C. Stere – EDP Bucharest 1980;

Shimizu M, Suzuki T, Kato S, Kojima Y, Yashiro K, Asakura T: Historic Tunnel Damage in Japan and Case Studies at Damaged Railway Tunnels - ITA-AITES 2007

Geotechnical Earthquake Engineering - Ikuo Towhatu

Introduction to Earthquake Engineering - S.Okamoto (1973)