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Waves, Vibrations and Structural Failures

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Outline

- 1978 Miyagi-ken-oki, Japan, earthquake: Slope failure
  K. Uenishi, *International Journal of Geomechanics*, 2010.

- 1995 Hyogo-ken Nanbu (Kobe), Japan, earthquake: Damage to underground structures
  K. Uenishi & S. Sakurai, *Earthquake Engineering and Structural Dynamics*, 2000.
  K. Uenishi & S. Sakurai, *Geomechanics and Tunnelling*, 2008.

- 1976 Friuli, Italy, earthquake: Failure of a group of surface structures
  K. Uenishi, *Rock Mechanics and Rock Engineering*, 2010.

Seismology

Some regard them literally as

- Shaking or structural vibrations in our living environments, either on the surface or in the ground

while others may be reminded of

- Wave propagation in solid earth.

In short, research in seismology has been developed to find more reasonable relations between the vibrations (records of seismographs) and "invisible" waves transmitted underground (and sometimes in the air).

However, the words "vibration" and "wave" are often confusedly used.

(K. Uenishi, *Pure and Applied Geophysics*, 2010)

Seismology

Late Professor Keiiti Aki (J. Seism. Soc. Jpn., 2005)

Two groups formed in seismology:

- Smooth earth club

Deterministic approach; "The earth's property is smoothly varying within bodies bounded by large-scale interfaces"; Traditional, long-period or low-pass filtered seismology.

- Rough earth club

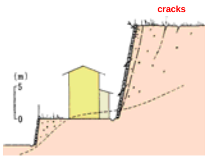
More recently developed stochastic approach, first applied by Professor Aki in 1969; Small-scale seismic heterogeneities of the lithosphere are inferred and accepted from the existence of coda waves in the seismological data set; Treating the scattering of short-period, or high-frequency seismic waves (frequencies more than 1 Hz) at small-scale heterogeneities.

Dynamic Slope Failure

The 1978 Miyagi-ken-oki, Japan, earthquake (M7.4)

One unique damage pattern was found at fill slopes in the Midorigaoka district of the residential area of Sendai City, located approximately 140km from the epicentre of the quake.

Cracks were found at positions some 6 meters away from the corner of the slope, whose inclination was some 75 degrees.



Typical failure of a fill slope in the Sendai city, induced by the 1978 Miyagi-ken-oki, Japan, earthquake.

Considering the epicentral distance (140km), it may be more appropriate to assume that the damage was induced by surface waves, especially Rayleigh waves, because surface waves may acquire an increasing preponderance at a great distance *r* from the source: Their attenuation from the source ($\sim 1/r^{1/2}$) is less than that of body waves ($\sim 1/r$).

Here, we shall analyse quantitatively the reflection and transmission of two-dimensional Rayleigh waves at the corner of a simple, wedge-shaped slope.

It will be shown that

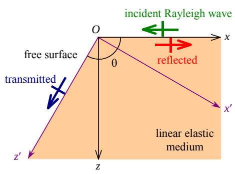
- The superimposition of the reflected and incident waves may induce strong stress amplification and generate open cracks at the top of the slope; and

- The effect of the inclination of slope is considerable.

Based on the method of Fourier transformations with the two Cartesian coordinate systems, we can evaluate quantitatively the effects of Rayleigh wave incidence on a wedge-shaped linear elastic slope.

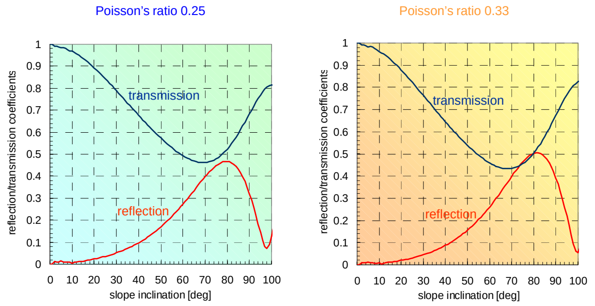
⇓

The position where the incident and reflected waves are in phase with each other (and therefore the superimposed amplitude becomes maximum) ⇒ Characteristics of the incident seismic waves

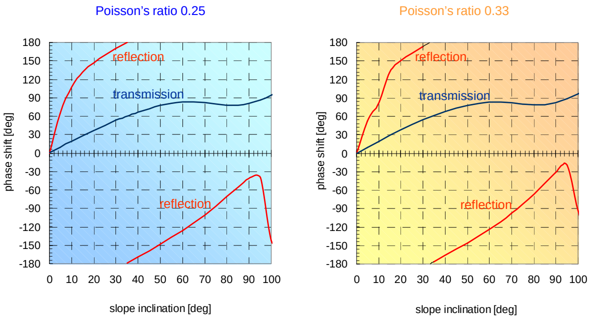


The two Cartesian coordinate systems employed in the analysis. The slope inclination is (180 − θ) degrees.

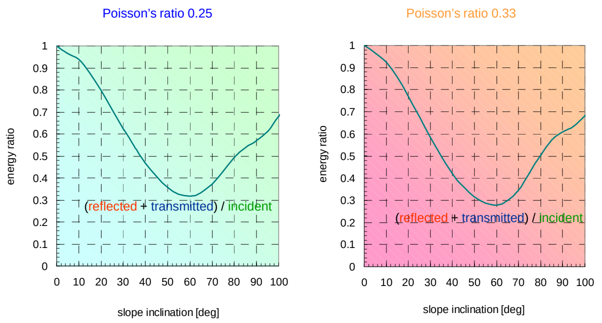
Effect of Slope Inclination



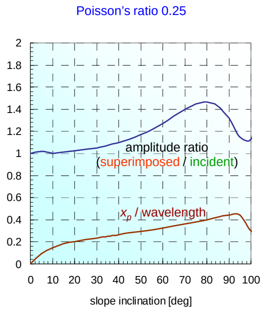
The effect of the slope inclination on the reflection and transmission coefficients.

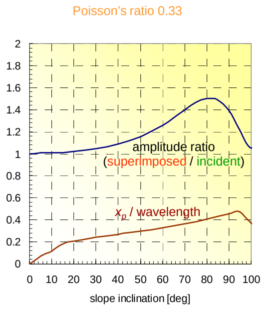


The relation between the slope inclination and the phase shift of the reflected and transmitted Rayleigh waves.



The effect of the slope inclination on the total energy of the reflected and transmitted Rayleigh waves.





The relation between the slope inclination and the normalised position x_p/wavelength where the incident and reflected Rayleigh waves are in phase and therefore the superimposed amplitude of those waves becomes maximum

Seismic Risk Assessment for Slopes

The simplest way of including seismic effects in the assessment of slope stabilities is to perform a limit equilibrium analysis where the dynamic, earthquake-induced force is replaced by static horizontal force.
Although this pseudo-static method has many limitations, it is widely used and some assessment criteria have been proposed (e.g., Fukuoka Prefecture Office, 1997).

Rank	Score	Potential
A	-1 or more	High
B	-6 to -2	Relatively high
C	-7 or less	Low

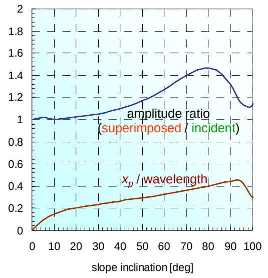
Inclination [deg]	Score
0-10	-5
11-20	-3
21-30	-1
31-40	+1
41-50	+2
51-60	+3
61-	+5

Monotonically increasing function?

In these assessments, basically, the effect of inclination is only qualitatively described and it is usually a rather crude "increasing function" with the inclination, i.e., the higher inclination is always more "dangerous" than the lower one.

Such tendencies can be seen also in our analysis, up to the inclination of 80 degrees, but the reflection coefficient is not simply proportional to the inclination even in that range, and it decreases significantly above 80 degrees.

$x_p = 0.38 V_R / f$
Rayleigh wave speed $V_R = 150$m/s
Wave frequency $f = 10$Hz
$\rightarrow x_p = 5.7$m



Therefore, more precise criteria including the quantitative information about the effect of the inclination might be needed in order to more effectively design earthquake-resistant slopes, especially those with higher inclination.

Remarks 1

The semi-analytical investigation on the dynamic behaviour of a wedge-shaped slope subjected to a Rayleigh wave has shown:

1. The surface wave can be amplified at the top of the slope most significantly when the slope inclination is some 80°. However, this amplification effect can be largely reduced by simply changing the angle to, say, 60° where much part of the incident wave energy is radiated in the form of body waves;

2. From the damage pattern observed on the occasion of the 1978 Miyagi-ken-oki, Japan, earthquake, the frequency of the incident seismic wave may be inversely evaluated. It was relatively high, 10 Hz containing both horizontal and vertical components of particle displacements (velocities, etc.); and

3. Conventional slope assessment criteria, based on pseudo-static earthquake forces, may generally provide correct tendencies, but the results obtained in this study might assist in designing earthquake-resistant slopes more quantitatively and effectively.

The 1995 Hyogo-ken Nanbu (Kobe) Earthquake

- 180,000 buildings on the surface
- Only a few underground facilities

Structural Damage 1

The Bantaki NATM Tunnel

- 1,766m-long, completed about four years before the earthquake;
- Damage in central section where it passes through a fractured zone;
- No distinct evidence of permanent ground deformation and fault displacement.

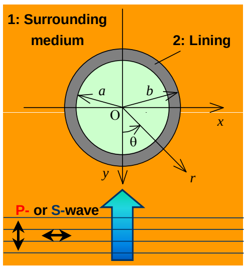
Failure Mechanism

The epicentre: only some 20km away

⇒ Interaction of high frequency components of the seismic waves with the tunnel before attenuation

Model Analysis

The Bantaki Tunnel: located deep in the mountains (granite)



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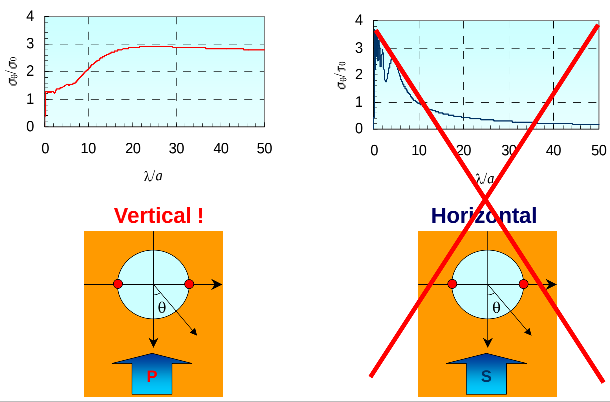
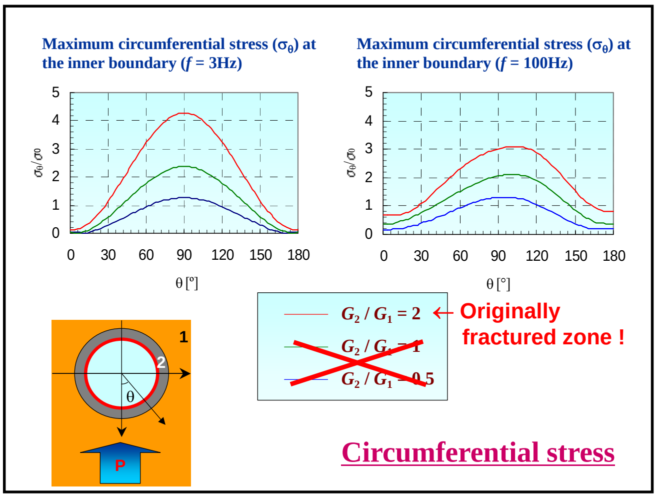
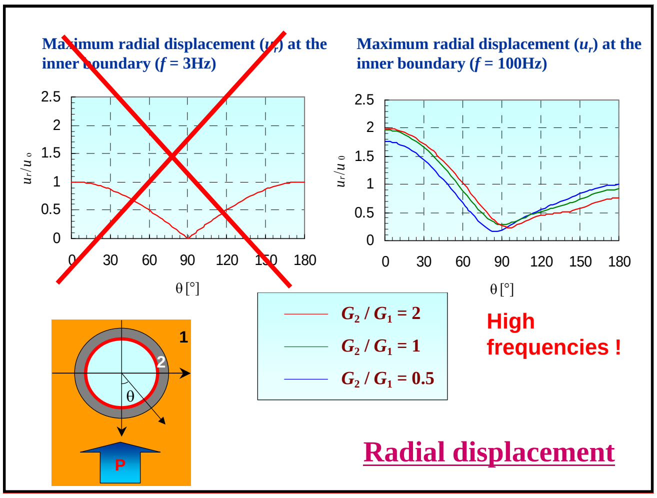
Dynamic process in terms of scalar and vector potential functions.

Vertical? Horizontal?

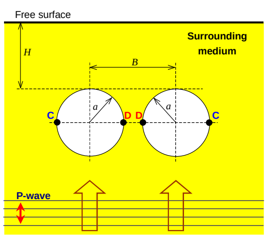


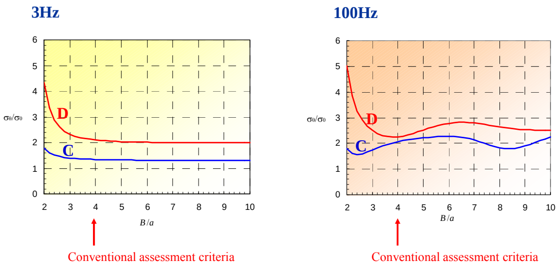


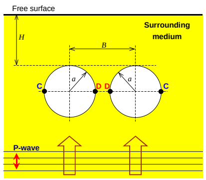


Dual Tunnels and the Overburden

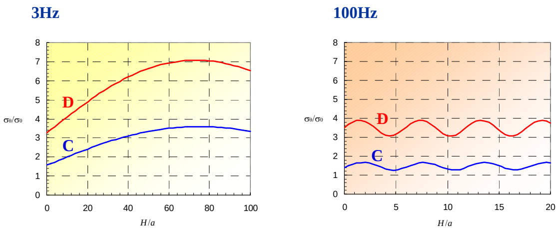
Since the number of dual tunnels - typically two tunnels running in parallel - is increasing, especially in urban areas, it may be important at this moment to investigate the effect of body waves on the mechanical behaviour of dual tunnels.

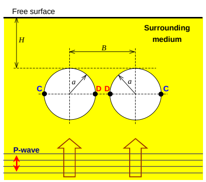






The maximum circumferential stresses, induced on the sidewall (at points **C**, **D**), vary with the distance *B*/*a* between the centres of the tunnels (overburden *H*/*a* = 1).



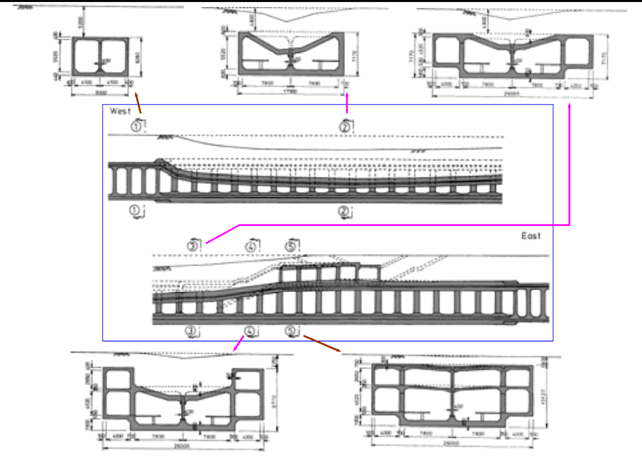


The relationship between the maximum circumferential stresses on the sidewall (at points **C**, **D**) and the overburden *H*/*a* (the distance between the centres of the tunnels *B*/*a* = 2.2).

Structural Damage 2

The Daikai Underground Station:

- Built by cut-and-cover methods, opened in 1968;
- Collapse of over 20 central columns induced subsidence of max. 2.5 m of the street above, with substantial settlement over an area of 100 m x 20 m;
- Aside from this collapse-induced movement, no distinct evidence of permanent ground deformation by other causes such as liquefaction.



Collapse of the Daikai Underground Station

Failure Mechanism

Failure in shear and/or bending due to horizontal vibrations

- Large shearing structural deformation:
  not expected in the underground;
- The columns at the Daikai Station:
  designed not to induce bending moments at their ends.

Buckling due to vertical impact

- Considerable vertical oscillations:
  caused failures of surface structures;
- The epicentre:
  only some 20km away.

⇒ Interaction of high frequency components of the vertical seismic waves with the tunnel before attenuation

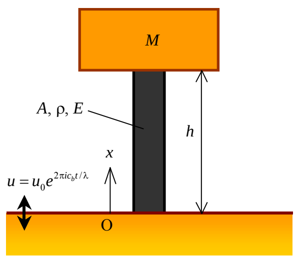
Model Analysis

A column supporting overburden M and subjected to vertical oscillations

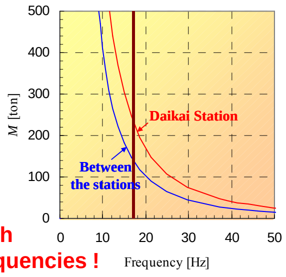
⇓

Resonance

$$2\pi M \sin\frac{2\pi h}{\lambda} - A\rho\lambda\cos\frac{2\pi h}{\lambda} = 0$$



Resonance



High frequencies !

The overburden supported by the central column at each section

Cross-section	Overburden *M* [ton]
1-1	90
2-2	225
3-3, 4-4	240
5-5	95

The relation between the resonant frequency of the incident wave and the overburden *M* in and near the Daikai Station.

Remarks 2

We investigated the behaviour of single and dual tunnels subjected to dynamic disturbances:

1. From the structural damage patterns observed on the occasion of two specific earthquakes in Japan, we "inversely" evaluated the dominant frequencies of relevant seismic waves.

2. The results suggest the existence of relatively high frequency components (over 10 Hz), and they might assist in designing more earthquake-resistant structures.

3. This study also suggests that, contrary to the structures on the surface, underground structures subjected to dynamic waves vibrate with their surroundings and they are expected to function as sensors that respond only to waves of specific type, frequency and propagation direction and detect higher frequency components of seismic waves.

Vibrations + Waves ⇔ Structural Collapse

Conventional analyses in engineering seismology:

Mechanical behaviour of each structure is usually treated separately;
Interaction between structural vibrations and the waves in the ground (rock mass, soil) is most often neglected,

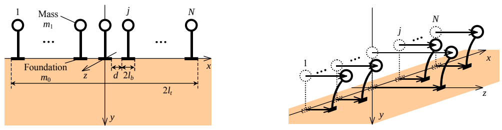
although structures, either on the surface or in the ground, do exist next to each other in a more developed environment, namely, in a town or a city.

Instead, the structure itself is assumed to consist of more complex and realistic components and the vibration characteristics are analysed in great detail.

However, at present, it is not so certain that these conventional methods are valid for analyzing the seismic performance of a group of structures densely built in an urban area.

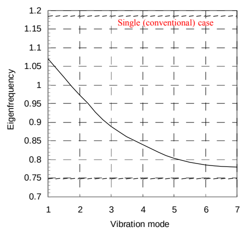
It may be difficult to conclude that the dynamic interaction between multiple structures and the waves propagating in the ground (structure-wave-structure interaction) is completely negligible.

The Town Effect

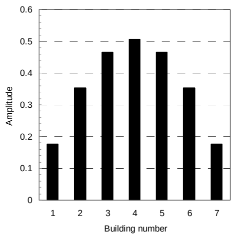


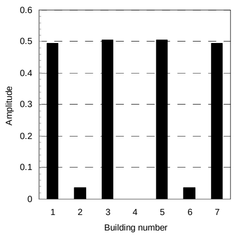
The "town model" employed in the analysis (modified after Ghergu and Ionescu 2009):

(left) N buildings are uniformly distributed on the flat surface of a linear elastic half-space (ground), with separation distance d. The total length of the town is $2l_t$, and each building j ($1 \le j \le N$) is represented by a rigid foundation (having width $2l_b$ but no height), a mass at the top and a linear elastic spring that connects the mass and foundation; and
(right) Due to dynamic interaction between the buildings and the anti-plane elastic waves in the ground, each foundation (and mass at the top) may behave mechanically differently even for a single vibration frequency of the town.



Normalised eigenfrequency ξ_k ($\equiv 2\pi f_k\, l_b/V_S$) related to each vibration mode k [$1 \le k \le N$ (= 7)] of a town consisting of seven identical buildings on a linear elastic half-space [$d/l_b = 0.4$, $h/l_b = 2$, $m_1/m_0 = 1.5$, $\rho_b/\rho = 0.1$ and $(V_S)_b/V_S = 1.5$]. (Uenishi, *Rock Mech. Rock Eng.*, 2010)

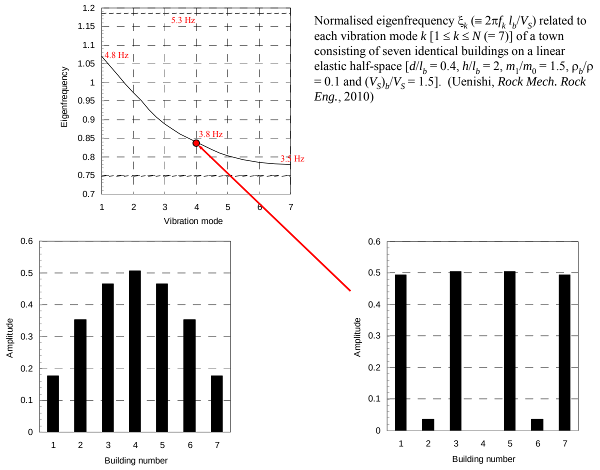




The 1976 Friuli, Italy, Earthquake

The original eigenfrequency of a single building with a rigid foundation may be evaluated approximately as f_0 = 5.3 Hz, if the observed V_S = 225 m/s and the length of each building $2l_b$ = 16 m (height h = 8 m) are employed.

The spectral response estimated for the TLM1 (Tolmezzo-Ambiesta dam) accelerograph site at the top of a calcareous hill from the main shock and aftershocks of this Friuli 1976-1977 earthquake sequence shows the dominant (peak) frequencies f_d of observed seismic waves near the epicentre to be about 2, 3.8, and 6-8 Hz.



Normalised eigenfrequency ξ_k ($\equiv 2\pi f_k l_b/V_S$) related to each vibration mode k [$1 \le k \le N$ ($= 7$)] of a town consisting of seven identical buildings on a linear elastic half-space [$d/l_b = 0.4$, $h/l_b = 2$, $m_1/m_0 = 1.5$, $\rho_b/\rho = 0.1$ and $(V_S)_b/V_S = 1.5$]. (Uenishi, *Rock Mech. Rock Eng.*, 2010)

Remarks 3

- It has been shown that the collective mechanical behaviour of a group of structures subjected to anti-plane horizontal displacements may be different from the ones expected through conventional seismic analyses that consider dynamic performance of each structure separately.
- As an example, the unique structural damage distribution generated in the Friuli region by the 1976 earthquake has been studied, and it has been suggested that the structures actually showed the dynamic collective coupled behaviour that may be called the "town effect" or "city effect."
- The purpose of the present contribution, however, is not to negate the important results obtained by conventional analyses of engineering seismology. The structural damage should be evaluated also from many other viewpoints like the amplitude and duration content of the dynamic motion at a site. Furthermore, the model employed here has many limitations: For example, the current study does not include the effect of rotation and vertical movement of the foundation of the building, and the foundation itself is rigid without any torsion and no damper (or similar mechanical models) is incorporated in the model.

(Semi-)Analytical Solutions

Surely, sophisticated numerical techniques will offer the opportunities to solve more specific, spatiotemporally complex and practical problems, but it does not mean that we can neglect the usefulness of analytical solutions.

As Professor Zimmerman states in *Fundamentals of Rock Mechanics, Fourth Edition* (2007), "Analytical solutions, although usually limited to simplified geometries, have the virtue of displaying the effect of the parameters of a problem, such as the elastic moduli or crack size in a clear and transparent way."

Until we have understood the basics, we will not be able to really appreciate the computational results obtained by fancy numerical simulations. This is an important fact nowadays we tend to forget.

(K. Uenishi, *Pure and Applied Geophysics*, 2009)