LECTURE 2
Catastrophic Vaiont Landslide, Italy.
Part 1

September 2017, Helsinki
Hendron and Patton (1987): “It is likely that more information has been published and more analyses have been made of the Vaiont data than for any other slide in the world”.

- Skempton, A.W. (1966) Bedding-plane slip, residual strength and the Vaiont landslide. Correspondence to Géotechnique, Vol. 16, No. 2, 82-84


Main references


I. VAIONT LANDSLIDE
I1. FAILURE DESCRIPTION

- Vaiont, 80 km North of Venice
- Vaiont River
- Height of arch dam: 276 m

- Catastrophic landslide (270 M m³) on October 1963 when the reservoir level was close to maximum
- Gigantic wave generated (220 m high)
- More than 2000 casualties
- Dam stood without breaking

(Valdés y Díaz-Caneja, 1964)
I1. Failure description

(Gabriel Fernández, 1979)
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11. Failure description

(Gabriel Fernández, 1979)
Longarone before the event

Longarone after the event
I1. Failure description

MAP OF VAIONT SLIDING AREA

Simplified from Belloni y Stefani (1987) with additional information from several authors
I1. Failure description

Relationship between precipitation, reservoir level, rate of movement and water level in “piezometers”

From Hendron y Patton (1985), based on a figure by Müller, (1964).
I1. Failure description


“...the shocks generated in the zone of the slide signify dilation of the material in a zone of sagging of the rock.”

(Nonveiller, 1987)
The **sliding surface** is located in strata of the upper Mälm period (upper Jurassic) constituted by **clays** and **marls**

**Above the sliding surface**: finely stratified layers of **marl** and **limestone**

**Below the sliding surface**: unaffected Jurassic **limestone** banks of the Dogger period
Tentative reconstruction of the paleo-slide of Vaiont

1: Situation before the first motion (end of last glaciation?);
2: First motion of the slope;
3: Process of progressive sliding (undulated continuous line) and rotational slides at the toe;
4: Successive erosion phenomena on the upper parts;
5: Ancient landslide and intense fracturing of strata. The valley is invaded by the gigantic slide.
6: The slide before November 4, 1960, after thousands of years of erosion. The river has cut a new, narrow gorge.
7: The profile after a “small” landslide on November 4, 1960;
8: The final shape of the cross section after the slide of October 8, 1963 (present situation). The inset shows an eroded part of the slide surface by the rapidly moving waters displaced by the slide.

(Simplified from Semenza, 2001)
12. Geology

Two representative cross-section of the landslide

(Cross Section 2)

(Cross Section 5)

(Hendron and Patton, 1985)
I3. The sliding surface

Thin continuous layers of high plasticity clay were consistently found in the position of the failure surface.

(Gabriel Fernández, 1979)
13. The sliding surface
I3. The sliding surface
I3. The sliding surface

(Gabriel Fernández, 1979)
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(Gabriel Fernández, 1979)
I3. The sliding surface

Plasticity of clay samples from the sliding surface

Atterberg limits without shear strength data
Atterberg limits with shear strength data ($\phi_r$ in degrees)
W – Waterways Experiment Station
K – Kenney (1967)
N_y – Nonveiller (1967)
T – Thurber Consultants
N – Nieto, University of Illinois

Liquid Limit (LL)

Plasticy Index (PI)

U-Line
A-Line
MH & 0H
ML & 0L

(Hendron y Patton, 1985)
I3. The sliding surface

Shear Stress of samples from Vaiont sliding surface

1. Hendron y Patton, 1985

- Direct shear strength of remoulded specimens (loading-unloading cycles)

Residual friction:

\[ \phi'_{res} = 10^\circ \]

2. Tika y Hutchinson, 1999

Ring shear test on a clay specimen from de vicinity of Vaiont sliding surface:

Static residual friction

\[ \sigma'_n = 500 \text{ kPa} ; \\
V = 0.0145 \text{ mm/min} \]
I4. Pore water pressure

Relationship between sliding rate, precipitation and reservoir level

(Hendron y Patton, 1985)
Relationship between water level in the reservoir and sliding velocity

(Gabriel Fernández, 2006)
II. CONVENTIONAL ANALYSIS
II1. Kinematics of sliding


The preceding account of the relevant information on Vaiont, indicates, however, that the friction angle at the failure surface could hardly be larger than 12°.
II. Conventional analysis

II2. Two block model

a) Initial state. Geometry and forces.

b) Geometry of the slide after a displacement $s$.

$V_{10} = 112590 \text{ m}^3/\text{m}$, $V_{20} = 93000 \text{ m}^3/\text{m}$,
II2. Two block model

Equilibrium to find the angle of basal shearing resistance

\[ \begin{align*}
\text{Block 1} & : \quad \begin{cases} 
W_1 \cos \alpha + F_i \sin(\alpha / 2) = N_1 \\
W_1 \sin \alpha = T_1 + F_i \cos(\alpha / 2) \\
T_1 = N'_1 \tan \phi'_b
\end{cases} \\
\text{Block 2} & : \quad \begin{cases} 
W_2 + F_i \sin(\alpha / 2) = N'_2 + U_2 \\
F_i \cos(\alpha / 2) = N'_2 \tan \phi'_b
\end{cases}
\end{align*} \]

\[
\frac{W_1(\sin \alpha - \cos \alpha \tan \phi'_b)}{\sin(\alpha / 2) \tan \phi'_b + \cos(\alpha / 2)} = \frac{(W_2 - U_2) \tan \phi'_b}{\cos(\alpha / 2) - \tan \phi'_b \sin(\alpha / 2)}
\]

\( \phi_b = 21.1^\circ \) if \( h_w = 120 \text{ m} \) (for water reservoir level=120m, October 1963)

\( \phi_b = 19.4^\circ \) if \( h_w = 60 \text{ m} \) (for water reservoir level= 60, November 1960)
II2. Two block model

\[ F = \frac{\tan(21.1^\circ)}{\tan(\varphi_{mob})} \]

**Safety factor**

a) Effect of water level (for zero slide displacement)

b) Effect of slide displacement for water level reservoir = 120 m
“The part of the stratigraphic column exposed in the slide mass consists of beds of partially crystalline limestones, limestones with hard siliceous inclusions, marly limestones and marls. Many beds are strongly folded and show indications of slope tectonics. Its geological structure but also its geological sequence has remained essentially unchanged. The entire rock mass remained intact and the sediment facies is nearly unchanged. Apart from some newly formed faults, the only other effects of the slide were the opening of existing joints and the development of new joints, resulting in an overall volume increase of 4-6% and an associated reduction of the mechanical coherence of the rock mass” (Müller, 1987)
II3. Two interacting wedges

- **Strength of intact material:** 50 MPa
- **Hoek Geological Strength Index, GSI = 50**
  (“very blocky, interlocked, partially disturbed, with multifaceted angular blocks formed by four or more joint sets”)
- **Hoek $m_i = 9$** (marls and soft limestone)
- **Degradation parameter:** $D = 0.5$ (in a scale 0 to 1)

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**Hoek-Brown Failure Criterion. Cross section between the two wedges**

- Mohr - Coulomb approximation ($\sigma_h = 2$ MPa)
- Mohr - Coulomb (zero cohesion)
- Hoek - Brown strength envelope
- Strength degradation

**Graph:**
- Shear strength vs. Normal stress
- $c' = 0.787$ MPa
- $\theta = 38.5^\circ$
II3. Two interacting wedges

- The upper and lower wedges changes their geometry during the sliding. Upper wedge (“unstable”) looses volume which is added to the lower one (“stable”). The common plane AB reduces in length during this process.

- Shearing across AB’ (τ = c’ + σ’ tan φ’). In addition, c’(s), (degradation of the cohesion dependents on the displacement ). φ’r is assumed to be constant.

- The lower sliding surface is assumed to be in residual conditions with strength parameters (c’ = 0; φ’b = 12°).

- Phreatic level is horizontal.

- Equilibrium condition are formulated in dynamic terms. Only inertia terms are considered.
II3. Two interacting wedges

**Upper wedge**

Equilibrium in direction parallel to motion

\[ W_1 \sin \alpha - T_1 - N'_\text{int} \cos(\alpha / 2) - Q'_\text{int} \sin(\alpha / 2) - U'_\text{int} \cos(\alpha / 2) = M_1 \frac{dv}{dt} \]
II3. Two interacting wedges

**Upper wedge**

Equilibrium in direction parallel to motion

\[ W_1 \sin \alpha - T_1 - N'_\text{int} \cos(\alpha/2) - Q'_\text{int} \sin(\alpha/2) - U'_\text{int} \cos(\alpha/2) = M_1 \frac{dv}{dt} \]

Equilibrium in direction normal to motion

\[ W_1 \cos \alpha + N'_\text{int} \sin(\alpha/2) + U'_\text{int} \sin(\alpha/2) - Q'_\text{int} \cos(\alpha/2) = N'_1 + U'_1 \]

\[ Q'_\text{int} = c'_r AB' + N'_\text{int} \tan(\phi'_r) \]

\[ T_1 = N'_1 \tan(\phi'_b) \]
II3. Two interacting wedges

Lower wedge

Equilibrium in direction parallel to motion

\[ N'_{\text{int}} \cos(\alpha/2) - Q_{\text{int}} \sin(\alpha/2) - T_2 = M_2 \frac{dv}{dt} \]
II3. Two interacting wedges

**Lower wedge**

Equilibrium in direction parallel to motion

\[ N'_{\text{int}} \cos(\alpha/2) - Q'_{\text{int}} \sin(\alpha/2) - T_2 = M_2 \frac{dv}{dt} \]

Equilibrium in direction normal to motion

\[ W_2 + N'_{\text{int}} \sin(\alpha/2) + U'_{\text{int}} \sin(\alpha/2) + Q'_{\text{int}} \cos(\alpha/2) + U_{f'y} = N'_2 + U_2 \]

**Motion equation**

\[ M^* \frac{dv}{dt} = W_1 s_1 - t_1 W_2^* + c' AB't_2 - U'_{\text{int}} t_3 + U_1 \tan(\phi'_b) \]
Mistake!!!
II3. Two interacting wedges

**Upper wedge**

Equilibrium in direction parallel to motion

Equilibrium in direction normal to motion

\[
W_1 \sin \alpha - T_1 - N_{\text{int}}' \cos(\alpha / 2) - Q_{\text{int}} \sin(\alpha / 2) - U_{\text{int}} \cos(\alpha / 2) = M_1 \frac{dv}{dt}
\]

\[
W_1 \cos \alpha + N_{\text{int}}' \sin(\alpha / 2) + U_{\text{int}} \sin(\alpha / 2) - Q_{\text{int}} \cos(\alpha / 2) = N_1' + U_1
\]

\[
Q_{\text{int}} = c_r AB' + N_{\text{int}}' \tan(\varphi'_r)
\]

\[
T_1 = N_1' \tan(\varphi_b)
\]
II3. Two interacting wedges

**Upper wedge**

Equilibrium in direction parallel to motion

Equilibrium in direction normal to motion

\[ W_1 \sin \alpha - T_1 - N'_\text{int} \cos(\alpha / 2) - Q'_\text{int} \sin(\alpha / 2) - U'_\text{int} \cos(\alpha / 2) = \frac{d(M_1v)}{dt} \]

\[ W_1 \cos \alpha + N'_\text{int} \sin(\alpha / 2) + U'_\text{int} \sin(\alpha / 2) - Q'_\text{int} \cos(\alpha / 2) = N'_1 + U_1 \]

\[ Q'_\text{int} = c'_r AB' + N'_\text{int} \tan(\varphi'_r) \]

\[ T_1 = N'_1 \tan(\varphi_b) \]

\[ \frac{d(M_1v)}{dt} = M_1 \frac{dv}{dt} + \frac{dM_1}{dt} v \]
II3. Two interacting wedges

**Lower wedge**

Equilibrium in direction parallel to motion

\[ N'_\text{int} \cos(\alpha/2) - Q_\text{int} \sin(\alpha/2) - T_2 = \frac{d(M_2v)}{dt} \]

Equilibrium in direction normal to motion

\[ W_2 + N'_\text{int} \sin(\alpha/2) + U_\text{int} \sin(\alpha/2) + Q_\text{int} \cos(\alpha/2) + U_{fy} = N'_2 + U_2 \]
II3. Two interacting wedges

Wedge mass variation

\[ AB' = \frac{L_0 / \cos \alpha - s}{L_0 / \cos \alpha} \frac{H_1}{\cos(\alpha/2)} \]

\[ V_{\text{Wedge 1}} = \frac{1}{2} \left( \frac{L_0}{\cos \alpha} - s \right)^2 \frac{H_1}{L_0} \cos \alpha \]

\[ \frac{dM_1}{dt} = \delta_r \frac{dV_{\text{Wedge 1}}}{dt} = -\delta_r \left( \frac{L_0}{\cos \alpha} - s \right) \frac{H_1}{L_0} \cos \alpha \frac{ds}{dt} \]
II3. Two interacting wedges

**Motion equation**

\[ s_5 \frac{d(M_1 v)}{dt} + s_2 \frac{d(M_2 v)}{dt} = W_1 t_1 + \left(W_2 - P_{w2} + P_{w_f} \right) t_2 + c'_{r} A B' t_3 - P_{wint} t_4 + P_{wl} t_5 \]

\[ t_1 = s_1 s_5 \]

\[ t_2 = \tan \varphi'_b s_2 \]

\[ t_3 = s_3 s_5 - s_2 s_6 \]

\[ t_4 = s_4 s_5 + s_7 s_2 \]

\[ t_5 = \tan \varphi'_b s_5 \]

\[ s_1 = \sin \alpha - \tan \varphi'_b \cos \alpha \]

\[ s_2 = \tan \varphi'_b \sin(\alpha / 2) - \cos(\alpha / 2) \tan \varphi'_r \tan \varphi'_b + \cos(\alpha / 2) + \sin(\alpha / 2) \tan \varphi'_r \]

\[ s_3 = \tan \varphi'_b \cos(\alpha / 2) - \sin(\alpha / 2) \]

\[ s_4 = \tan \varphi'_b \sin(\alpha / 2) + \cos(\alpha / 2) \]
II3. Two interacting wedges

Static equilibrium \((dv/dt = 0)\) at failure:

<table>
<thead>
<tr>
<th></th>
<th>(H_0) (m)</th>
<th>(H_1) (m)</th>
<th>(L_0) (m)</th>
<th>(L_1) (m)</th>
<th>(L_2) (m)</th>
<th>(\alpha) (°)</th>
<th>(\delta) (°)</th>
<th>(V_1) (m³/m)</th>
<th>(V_2) (m³/m)</th>
</tr>
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<tbody>
<tr>
<td>Section 2</td>
<td>580</td>
<td>245</td>
<td>750</td>
<td>190</td>
<td>260</td>
<td>37.7</td>
<td>43.3</td>
<td>116142</td>
<td>68149</td>
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<tr>
<td>Section 5</td>
<td>510</td>
<td>260</td>
<td>700</td>
<td>240</td>
<td>320</td>
<td>36</td>
<td>39.1</td>
<td>112590</td>
<td>93000</td>
</tr>
</tbody>
</table>

Strength parameters across shearing plane \(AB\) for equilibrium, Section 2 and 5. Basal friction: \(\varphi'_b = 12^\circ\).

Equilibrium in Section 5:

\(\varphi'_b = 12^\circ;\)
\(c'_r = 762.3\) kPa; \(\varphi'_r = 38^\circ\)
\(h_w = 120m\)
II3. Two interacting wedges

**Safety factors**

\[
\tan \varphi_{b_{mob}} = \frac{\tan \varphi'_b}{F_b}; \quad \tan \varphi_{r_{mob}} = \frac{\tan \varphi'_r}{F_r}; \quad c'_{r_{mob}} = \frac{c'_r}{F_r}
\]
II3. Two interacting wedges

### Safety factors

\[
\tan \varphi_{b\text{mob}} = \frac{\tan \varphi'_b}{F_b}; \quad \tan \varphi_{r\text{mob}} = \frac{\tan \varphi'_r}{F_r}; \quad c_{r\text{mob}} = \frac{c'_r}{F_r}
\]

1. If \( \varphi'_b = 12^\circ \) (i.e.: \( F_b = 1 \)) ¿What is the value of \( F_r \)?

**Equilibrium equation for the mobilized strength.**

\[
c'_r = \frac{-W_1 t_1 (F_r, F_b) - \left( W_2 - P_{w2} + P_{wf} \right) t_2 (F_r, F_b) + P_{wint} t_4 (F_r, F_b) - P_{w1} t_5 (F_r, F_b)}{AB' t_3 (F_r, F_b)}
\]

(Second order polynomial equation for \( F_r \), if \( F_b \) is assumed to be known)
Safety factors

\[ \tan \varphi_{b_{mob}} = \frac{\tan \varphi'_b}{F_b}; \quad \tan \varphi_{r_{mob}} = \frac{\tan \varphi'_r}{F_r}; \quad \frac{c'_{r_{mob}}}{F_r} = \frac{c'_r}{F_r} \]

1. If \( \varphi'_b = 12^\circ \) (i.e.: \( F_b = 1 \)) ¿What is the value of \( F_r \)?

Equilibrium equation for the mobilized strength.

\[
\frac{c'_r}{F_r} = \frac{-W_{1}t_{1}(F_r, F_b) - \left(W_2 - P_{w2} + P_{wf,r}\right) t_{2}(F_r, F_b) + P_{wint} t_{4}(F_r, F_b) - P_{w1}t_{5}(F_r, F_b)}{A B't_3(F_r, F_b)}
\]

(Second order polynomial equation for \( F_r \), if \( F_b \) is assumed to be known)

2. If \( (F_b = F_r = F) \), ¿What is the value of \( F \), the global safety factor?

(Eq. (1) is a fourth order equation: numerical solution)
II3. Two interacting wedges

**Effect of reservoir elevation.** Section 5

**Effect of slide displacement (for $h_w = 120$ m).** Section 5
II. Conventional analysis

II4. Landslide run out

**Motion equation**

\[ a = \frac{dv}{dt} = f(s) = f(\int_0^t v \, dt) \]

\( f(s) \) includes information of geometry, weights, pore water pressure, strength.

**Degradation model for cohesion along the shear plane between wedges.**

\[ c'_r = c'_{r0} \exp(-\Gamma s) \]
Calculated run outs and slide velocities when the water level is increased by different amounts from $h_w = 120$ m (strict equilibrium).

No rock strength degradation: $\Gamma = 0$
Calculated run out and slide velocities when the water level is increased one meter. Effect of rock strength degradation.

Moderate degradation: $\Gamma = 0.01$
Calculated run out and slide velocities when the water level is increased one meter. Effect of rock strength degradation.

Rapid degradation: $\Gamma = 1$

Section 5
III. CONCLUSIONS
III. Conclusions

1. Paleo-slides are associated with low safety factors. Small changes in boundary conditions induce instability.

2. Impoundment of the toe of slopes usually leads to a reduction of stability. The variation of safety factor depends on geometry of both the slope and the sliding surface.

**Vaiont: Changes of global safety factor with water level of the reservoir. (Phreatic level assumed horizontal)**

Section 5

In the case of Vaiont, F never had the opportunity to increase!
3. The conceptual model accepted to describe and predict the evolution of Vaiont landslide was not based on any mechanical analysis. Pore water pressure in the sliding surface, its position an geometry, type of material being sheared and its strength properties were unknown.

4. Managing a very large landslide is a daunting task. Carlo Semenza words:

“...things are probably bigger than us and there are no adequate practical measures...”...After so many fortunate works and so many structures ... I am in front of a thing which due to its dimensions seems to escape from our hands...” (in a letter written in April 1961, quoted by Nonveiller, 1987; the full letter (in Italian) was published in Semenza, 2001).
II5. Conclusions

**Safety Factor variation with reservoir level**

**a)** Vaiont geometry and \( (c' = 0; \phi' = 12^\circ) \)

**b)** Modified geometry from a) \( y (c' = 0; \phi' = 15^\circ) \)

**c)** Conventional geometry, circular failure and \( (c' = 0; \phi' = 30^\circ) \)
13. The sliding surface

Ring shear tests on a clay specimen from the vicinity of Vaiont sliding surface.

- **a)** Static residual friction determined at a shearing rate of 0.0145 mm/min

- **b)** Effect of shearing rate.

(Tika and Hutchinson, 1999)