POLITECNICO DI TORINO

Corso di Laurea Magistrale in Ingegneria Civile

Master Thesis

Earthquake risk assessment through BIM

Crodo

Scuola elementare

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Abstract:

Earthquakes are among the most significant natural hazards that threaten the safety and stability of urban infrastructure and buildings. Among these, public-use buildings, particularly schools, hold a special place in the assessment and management of seismic risk. Schools, due to their crucial role in educating future generations and the high concentration of individuals (students and staff) in a confined space, are considered one of the most sensitive types of buildings to seismic hazards.

Older buildings, constructed according to past design and construction standards, often lack modern earthquake-resistant criteria. This highlights the urgent need to analyze the structural conditions and assess the seismic risk of such buildings. Furthermore, the collapse or severe damage to school buildings can have profound impacts on the community, endangering lives, disrupting educational processes, and increasing reconstruction costs.

This thesis aims to assess the seismic risk of an old building used as a school. The research seeks to identify structural vulnerabilities, evaluate the level of risk, and propose mitigation solutions, contributing to the enhancement of safety for similar buildings. The research methodology includes reviewing the building’s technical documentation, structural modeling using specialized software, and evaluating different seismic scenarios.

The results of this study can serve as a guide for decision-making regarding the retrofitting, demolition, or redesign of similar school buildings. Ultimately, the study aims to reduce the vulnerability of schools to earthquakes and ensure greater safety for students and school staff.

Chapter 1:

1. Introduction

1.1. Location:

This report examines the static and environmental risks of an elementary school in Crodo, located in the Piemonte region. The site is in the province of Piemonte, northeast of Domodossola, and near the Swiss border.

- Foppiano di Crodo & Bouldering

Foppiano di Crodo is a location in the Province of Verbano-Cusio-Ossola, within the Ossola Valley.

The area is particularly famous among bouldering enthusiasts due to the presence of large glacial boulders scattered throughout the woodland.

The "Sass Fendù" (meaning "Split Rock" in the local dialect) is one of the most well-known boulders in the area, attracting climbers from Italy and beyond.

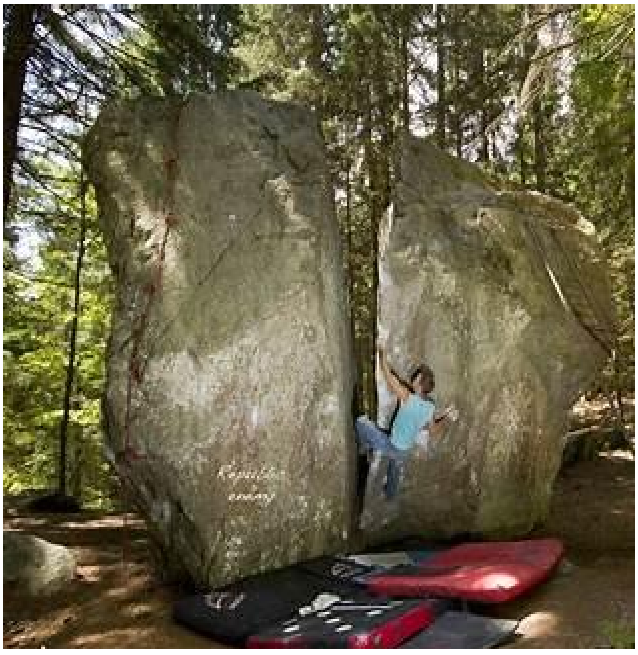


Figure 1. The sample of Sass Fendù

- The Toce River

The Toce River is a significant watercourse in northern Italy, flowing through Val d’Ossola before joining the Ticino River.

It is well known for the Cascata del Toce (Toce Waterfall), one of the most spectacular waterfalls in the Alps, located upstream near Formazza.

- Torrente Alfenza

The Torrente Alfenza is a small creek that also flows through the region and is considered an important tributary of the Toce.

These smaller watercourses often play a key role in the hydrology of the region, particularly in mountainous areas.

1.1.1. Origin and Stability of the Boulders

The boulders in this area are likely glacial erratics, meaning they were transported and deposited by ancient glaciers.

Some could also be rockfall deposits, meaning they detached from cliffs or slopes above and rolled down.

If these boulders are already stable and well-embedded in the soil, they pose little immediate risk.

However, if they rest on unstable ground (such as loose soil or sloping terrain), they could be prone to movement, especially after heavy rainfall or seismic activity.

1.1.2. Natural Hazards That Could Affect Boulder Stability

Landslides & Rockfalls: If the area has steep slopes, changes in vegetation, or erosion from the Toce River and Alfenza Creek, boulders might become destabilized.

Seismic Activity: Northern Italy, including the Alps, experiences some seismic activity. Even small tremors could dislodge boulders. That discus about later.

Soil Erosion & Water Flow: Water from the river and creeks could gradually undercut soil supporting the boulders, increasing the risk of movement.

1.1.3. Risk to Old Buildings

Many older buildings in mountain villages are made of stone and mortar, which may be weaker than modern reinforced concrete structures.
If a boulder moves due to any of the above factors, it could:

- Cause direct structural damage if it rolls or falls onto a building.
- Lead to foundation instability if it shifts soil near building foundations.
- Block drainage channels, increasing flood risks.

Potential Risks to Old Buildings:

Structural Vulnerability: Older buildings, often constructed with traditional materials and methods, may not be designed to withstand dynamic impacts from rockfalls. The force exerted by even a small boulder can cause significant structural damage.

Historical Precedents: While specific events in Foppiano di Crodo are not documented, other regions have experienced destructive rockfalls. For instance, in South Tyrol, Italy, massive boulders have destroyed buildings, leaving visible scars on the landscape.

Mitigation Strategies:

- That all these below are suggested.

To safeguard old buildings from potential rockfall damage, we can consider the following approaches:

Rockfall Hazard Assessment:

Detailed Mapping: Conduct surveys to identify potential rockfall source areas and existing boulders that might become unstable.

Historical Analysis: Review any available records or local anecdotes about past rockfall events.

Protective Measures:

Barriers and Nets: Install rockfall barriers or nets uphill from vulnerable structures to intercept falling rocks.

Deflection Structures: Construct walls or berms to divert potential rockfall paths away from buildings.

Monitoring and Early Warning:

Regular Inspections: Periodically check the stability of nearby boulders, especially after extreme weather events.

Technological Monitoring: Employ devices to detect ground movement or vibrations indicative of potential rockfalls.

Community Engagement and Preparedness:

Local Knowledge: Engage with local residents to gather information on past events and areas of concern.

Emergency Planning: Develop and communicate evacuation plans in case of a significant rockfall event.

In the district “Foppiano di Crodo” there's a woodland that is famous for the many boulders that were found among the trees. In fact, the area is a notorious climbing spot among bouldering climbers and the boulder "Sass Fendù" has become a symbol of this place.

- On the east side, away from the school, there is river it called Toce, can see in Figure 1. Also, according to better investigation we find a small creek that is as well as the river of Toce important, which is called "torrente Alfenza".
- In the same side the distance from the main road of village is about 250(m), as we can see in Figure 2.
- As we can see in Figure 3., the topography of the area shows us, the school between river and the high hills those are in west side, (or better say the behind of the school), is located.

Figure 2. Topography of the area and position of the school

1.2. Investigating possible risks:

1.2.1. Building risks itself:

In order to find and evaluate the static risks, which affects the building itself, two very important points should be mentioned.

According to reports from 1816 to 1940, sourced from the documents of *Archivio di stato di Novara, genio Civile, inventario (1861-1986),* this area was once part of Novara. The building was not originally designed for school use but initially belonged to the municipality. Therefore, the total weight of the structure, the stairs, and the emergency exit should be considered, as they do not meet the specifications for the number of children and teachers.

Due to the age of the building, when it was built, used of local materials, which may had lost its effectiveness now after years.

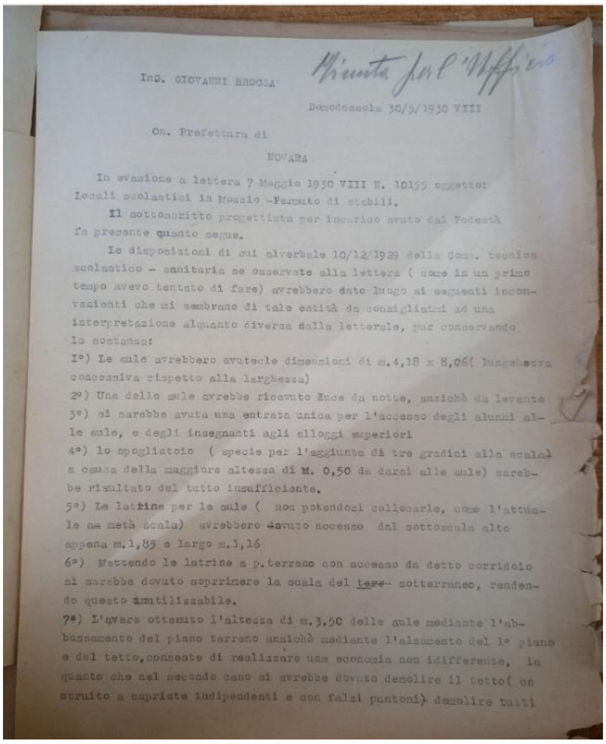
Also, according to reports (photos of documents), in 1929 the building had been about to collapse (specially in basement and ground level), which has forced to raise the ceiling to a height of 3.5(m), and the cause is excessive humidity. In the existing photos such the picture below, therefore, the building needed to be renovated many times.

Figure 3. The renovated of building

Another notable point, which is certainly not statical problem, but has been noticed many times in the process of reconstruction, is the poor state of sanitation and toilet (such as the toilets were mixed, as mentioned in the 1930 report), and of course its latest condition cannot be checked accurately in recent photos. There is also another group of mainly architectural problems reported in the reports, some of which have been resolved during the renovation of the building over the years, while, others still remain. A list of them is given below:

- In the classrooms, the proportional length of the class to its width is small.
- One of the classrooms does not have enough light.
- There is only one entrance to the building.
- The floor of the first floor or actually the ceiling of the ground floor should be demolished.
- A dressing room needs to be added at the beginning of the staircase.
- Changing the walls and wooden windows frames.

we should discuss about: architecture, in term of health and hygiene.



Ing. GIOVANNI BROGGA

Minuta per l'Ufficio

Domodossola 30/5/1930 VIII

On. Prefettura di

NOVARA

In evasione a lettera 7 Maggio 1930 VIII N. 10155 oggetto: Locali scolastici in Mozzio -Permuto di stabili.

Il sottoscritto progettista per incarico avuto dal Podestà fa presente quanto segue.

Le disposizioni di cui al verbale 10/12/1929 della Comm. tecnica scolastico - sanitaria se osservate alla lettera (come in un primo tempo avevo tentato di fare) avrebbero dato luogo ai seguenti inconvenienti che mi sembrano di tale entità da consigliarmi ad una interpretazione alquanto diversa dalla letterale, pur conservando la sostanza:

I°) Le aule avrebbero avute le dimensioni di m.4,18 x 8,06(lunghezza eccessiva rispetto alla larghezza)

2°) Una delle aule avrebbe ricevuto luce da notte, anzichè da levante

3°) si sarebbe avuta una entrata unica per l'accesso degli alunni alle aule, e degli insegnanti agli alloggi superiori

4°) lo spogliatoio (specie per l'aggiunta di tre gradini alla scala) a causa della maggiore altezza di M. 0,50 da darsi alle aule) sarebbe risultato del tutto insufficiente.

5°) Le latrine per le aule (non potendosi collocarle, come l'attuale a metà scala) avrebbero avuto accesso dal sottoscala alto appena m.1,85 e largo m.1,16

6°) Mettendo le latrine a p.terreno con accesso da detto corridoio si sarebbe dovuto sopprimere la scala del ~~terr~~- sotterraneo, rendendo questo inutilizzabile.

7°) L'avere ottenuto l'altezza di m.3,50 delle aule mediante l'abbassamento del piano terreno anzichè mediante l'alzamento del 1° piano e del tetto, consente di realizzare una economia non indifferente, in quanto che nel secondo caso si avrebbe dovuto demolire il tetto(costruito a capriate indipendenti e con falsi puntoni) demolire tutti

Figure 4. The architecture change of building

1.3. Static and environmental risks:

The risks have been categorized in the following order:

- **Floods**
- **Earthquake**
- **landslides**

Here, the focus is on earthquake and landslide risks:

1.3.1. Floods

To assess the risks related to floods and landslides, the available reports from previous years were first reviewed, followed by an analysis of the flood potential in recent years based on the rainfall chart. The reports highlight frequent flooding events, particularly in 1924, 1948, 1951, and 1957 in this area. Additionally, it is known that the Toce River overflowed in 2021, which should be noted as a significant event. Behind the building, the humidity in the cement walls is high, the basement is damp and deteriorating. In the western and northern parts of the building, surface water needs to be collected and diverted, and drainage is required, as shown in the picture.

Figure 5. The humidity of the cement walls

Due to the proximity of the river to the building, the structure is always at-risk during flooding events. The main road has also been problematic, and it seems necessary to install a protective wall. It should be noted that the issue appears to remain unresolved, as seen in the aerial photos of the area (further investigations are needed). A comparison of the precipitation graph from August of last year with this year shows an increase of 30 mm in precipitation, indicating that the river's water level has risen accordingly, which increases the likelihood of flooding. However, for an accurate assessment, it is necessary to review and compare these statistics across different months and years.

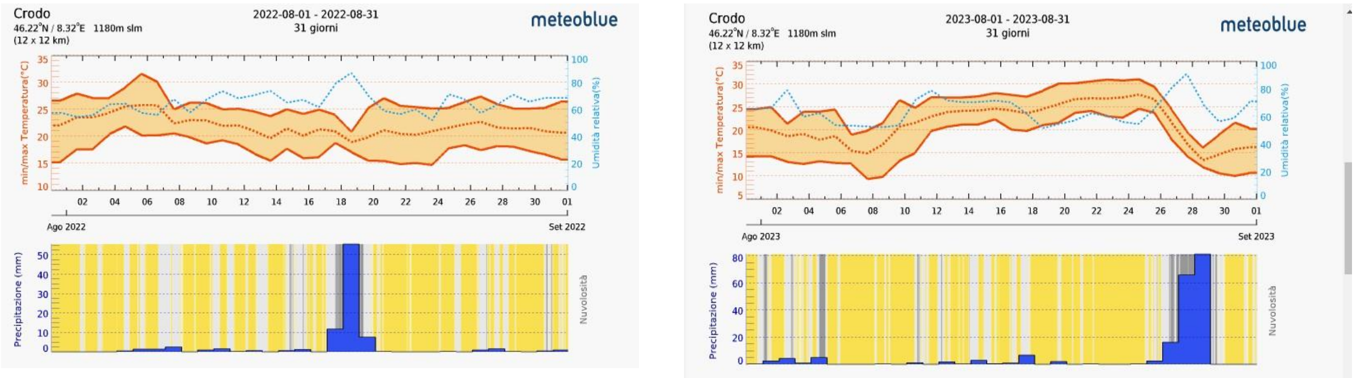


Figure 6. The comparison rainfall between Agust-2022 and Agust-2023

Additionally, according to this chart (Figure 6), the humidity and air temperature can be compared during the hottest month of the year. This shows that as precipitation increases, there is a decrease in temperature and an increase in humidity.

1.3.2. Earthquake

Incorporating an analysis of seismic activity in Italy, particularly within the Lombardy region, is crucial for a comprehensive risk assessment of the elementary school in Crodo. Understanding the seismic classification and potential hazards can inform structural stability assessments and the development of effective mitigation strategies.

Italy is divided into four seismic zones, each representing a different level of seismic hazard:

Zone 1: High seismicity; includes municipalities with significant seismic activity.

Zone 2: Medium-high seismicity; encompasses areas with considerable seismic risk.

Zone 3: Medium-low seismicity; covers regions with moderate seismic hazard.

Zone 4: Low seismicity; includes areas with minimal seismic risk.

These classifications are based on the expected peak ground acceleration (PGA) and help determine the necessary building codes and safety measures.

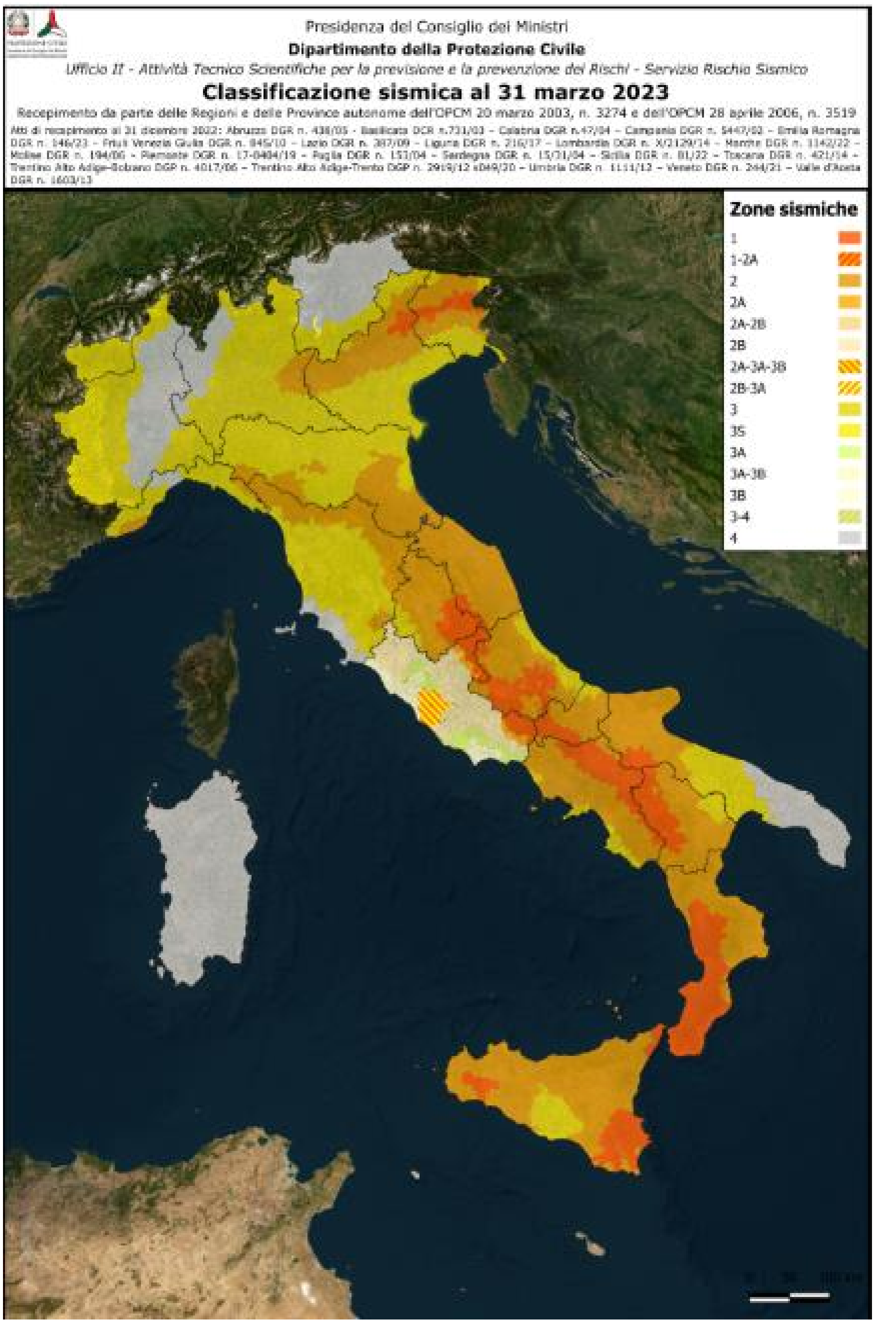


Figure 7. Seismological map

- **Seismic Hazard in Lombardy**

The Lombardy region predominantly falls under Zones 2 and 3, indicating medium to medium-low seismicity:

<u>Zone 2:</u> Encompasses 57 municipalities, primarily in the central-eastern part of Lombardy, including areas in the provinces of Mantua and Brescia.

<u>Zone 3:</u> Covers 1,025 municipalities across the region.

Notably, the municipality of Crodo is situated in the Province of Verbano-Cusio-Ossola, which is classified under Zone 3, indicating a medium-low seismic hazard.

- **Implications for Structural Stability**

Given Crodo's classification in Zone 3, the elementary school should be designed and assessed to withstand modest seismic events. While the seismic risk is not as high as in Zone 1 or 2 areas, it is essential to ensure that the building adheres to the seismic design criteria specified for Zone 3. This includes implementing structural reinforcements and using materials that can endure potential ground movements.

- **Recommendations for Risk Mitigation**

Regular Structural Assessments: Conduct periodic evaluations to identify and address any vulnerabilities in the building's structure.
Seismic Retrofitting: Implement necessary upgrades to enhance the building's resilience against seismic activities.
Emergency Preparedness: Develop and regularly update emergency response plans, ensuring that staff and students are trained to respond effectively during an earthquake.
By acknowledging the seismic characteristics of the Lombardy region and specifically Crodo's classification, the risk assessment becomes more robust, leading to informed decisions that prioritize the safety and well-being of the school's occupants.
The Reference is, Seismic Classification," *Dipartimento della Protezione Civile* ", that mention the link in references.

1.3.3. Landslides

- Even though we have two staircases in the building and the numbers of students are not so much, a lack of the emergency exit, is the problem still persists.
- The seismological map in Italy shows that this zone, is not in the high-risk area, but this does not mean there is no need to protect the structure against earthquake, specially, we are facing with the old structure, that could be need more protect in some cases.
- On the other hand, it seems necessary to check the type of soil according to the proximity to the river bed for more accurate calculations of earthquake factors.

Another issue that we should pay attention to here is, Landslides and stones falling from the boulders the necessity of having a supporting wall in the back yard and the area added to the building.

1.4. Wind

Based on the 2022 storm report in the Novara region, it is necessary to briefly review the wind intensity during the spring, when winds are typically strong. This case study was estimated on April 9, 2022, when wind intensity reached approximately 60 km/h, as shown in Figures 9 and 10.
Therefore, it is useful to examine the calculation for this potential risk as well.

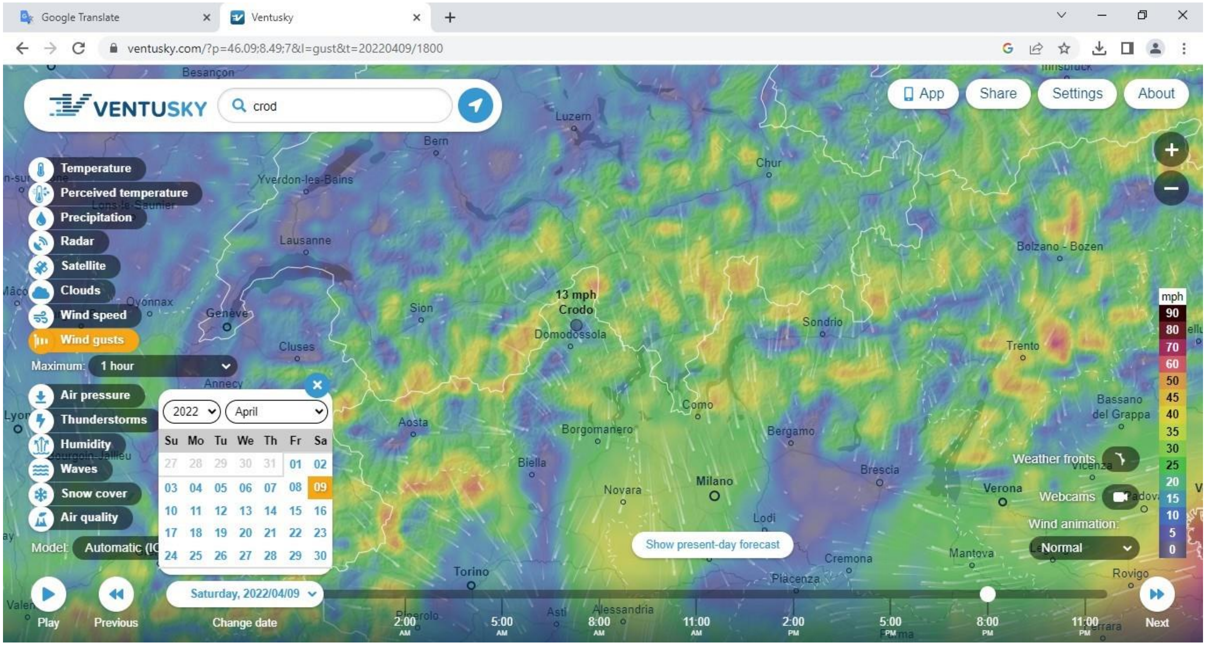


Figure 8. Wind intensity sample (09 April 2022), Heatmap

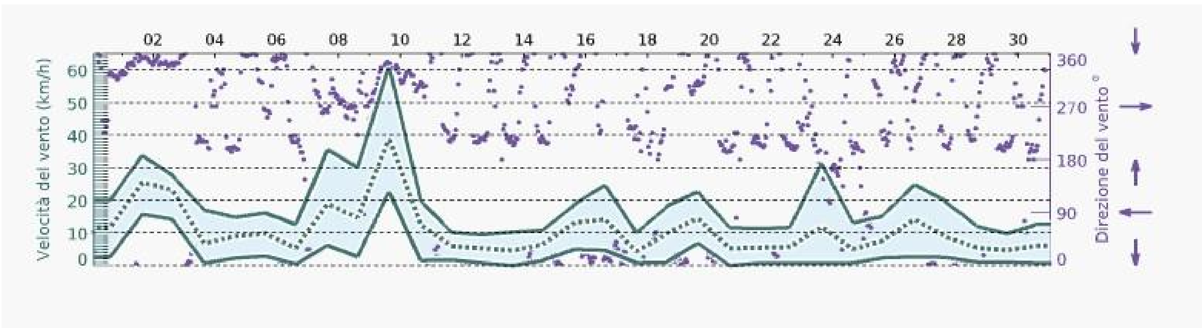


Figure9. Wind intensity sample (09 April 2022), Line chart

Chapter 2:

2. Structural stability assessment

This chapter will focus on the calculation of the control of stability of building foundation.

The first step requires information about soil characteristics, which can be found in the soil mechanics report. However, since this report is not available, some parameters will be assumed. In any case, the necessary information regarding soil type and condition will be listed.

However, from the geographic of this area and the pictures that are available in the project, and by considering the past documents of this building, I can find which calculations are fundamental, in any case, the essential calculation, should be done.

2.1. Soil Calculation

Soil calculation plays a crucial role in geotechnical engineering, ensuring the stability and safety of structures built on or within the ground. Understanding soil properties helps engineers determine the appropriate foundation design, assess potential risks, and optimize construction methods. Several key aspects are considered in soil calculations:

- Soil investigation
- Soil type
- Bearing capacity
- Shear strength of soil

All above, should be consider, but the point is, all of them they are fundamental concept, that they must be localized for our project, for example the bearing capacity, should be clear for which type of foundation will be use, however we will see in the next step how we can consider of all these parameters in our calculation.

2.2. Foundation

Generally, now, we should design the foundation, but in our project, the foundation is existed, therefore, I just consider, according the all documents that I verified before, I assume that, we can have a shallow foundation, since anyway the foundation is on the stone area. Here I should consider also of the load distribution, that is not quite clear, but knowing that how the load distributed on the foundation.

Note: We should consider repairing or strengthening the existing foundation. Additionally, the existing reinforcement should be taken into account.

2.3. Structural load

It's for sure to take into account to the weight of the building, considering of the dimension and layout. I should verify all documents plans, all the reinforcement documents, also, pay attention to the live load and ext.

2.4. Environmental condition

That is obvious. Consideration should be given to the water level, the groundwater level, the drainage system, and also an assessment of the climate and weather.

2.5. Settlement

This is an important factor in understanding the current condition of the building. A thorough knowledge of all past settlements and their impact on the building at present is essential.

2.6. Seismic

This was briefly considered in Chapter 1. Now, a more detailed analysis is needed, as this subject has a significant impact on all parameters of stability control.

2.7. Maintenance

Here takes attention into the all maintenance or all repair that happen before or every change of the use of the building.

Chapter 3:

3. Stability control measures and risk mitigation

From another perspective, controlling the stability of a building's foundation involves considering various factors and consulting with a structural or geotechnical engineer. The following key factors are highly recommended for a thorough evaluation and appropriate recommendations. It is essential to assess and, if necessary, implement control measures for.

3.1. Soil Condition

Understand the type and properties of the soil beneath the foundation. Different soils have different load-bearing capacities, and their stability can affect the foundation's performance. Assessing the soil condition involves considering various parameters that help determine its properties and how it may affect the stability of a foundation. Here are key parameters to consider.

3.1.1. Soil Type

Identify the type of soil, such as clay, silt, sand, gravel, or a combination (loam). Each soil type has different properties, including particle size distribution and water retention capacity. The soil type, could be:

1. Gravel (G)
2. Sand (S)
3.Silt (M)
4.Clay (C)

Modifiers provide additional information about the soil's properties, such as plasticity or organic content. Some common modifiers include:

W: Well-graded
P: Poorly-graded
O: Organic
H: High plasticity
L: Low plasticity

The combination of the primary soil type symbol and any modifiers gives a comprehensive description of the soil. For example:

GW: Well-graded gravel
CL: Low plasticity clay
SM: Silty sand

3.1.2. Soil Density

Measure the density of the soil, which indicates how closely packed the soil particles are. Compacted soil generally has higher density and better load-bearing capacity.

$$\rho = \frac{mass(kg)}{volume\ (m^3)}$$

$$\rho = \frac{mass(lb)}{volume\ (f_t^3)}$$

Unit: kg/m^3

3.1.3. Moisture Content

Determine the amount of water present in the soil. Soil moisture affects its volume and strength. Excessively wet or dry soil can lead to instability.

(Mass of water in the soil/dry mass of the soil) x100

Symbol of coefficient: MC

Unit: %

3.1.4 Compaction Characteristics

Assess the soil's compaction characteristics, which indicate how well the soil particles are bonded together. Properly compacted soil provides better support for foundations.

Bulk Density and Maximum Dry Density = (Mass of Dry soil/Volume of soil)

Unit: (kg/m^3) or (lb/ft^3)

3.1.5. Shear Strength

Evaluate the shear strength of the soil, which is its ability to resist deformation under stress. This is particularly important for assessing the soil's stability against sliding or failure.

$$\text{Shear Strength}(\tau) = \frac{\text{Area (in square feet or square inches)}}{\text{Force (in pounds)}}$$

<u>Symbol of coefficient</u>: (τ)

Unit: (Pa) or (MPa)

3.1.6. Permeability

Determine the soil's permeability, which is its ability to allow water to pass through. Highly permeable soils may be prone to water-related issues, while low permeability can lead to poor drainage.

$$k = \frac{Q}{A.H.\Delta P}$$

K: is the coefficient of permeability (hydraulic conductivity),
Q: is the volume of water flow (discharge) through the soil,
A: is the cross-sectional area through which the water flows,
H: is the height of the soil specimen,
ΔP: is the change in hydraulic head across the soil specimen.

Unit: (m^3/s/Pa) or (mm/s) or
(gpd/ft^2/ft) or (in/h).

3.1.7. Bearing Capacity

Calculate the bearing capacity of the soil, representing the maximum load it can support without failure. This is a critical parameter for designing foundations. The Terzaghi bearing capacity equation is typically applied to shallow foundations (footings) on cohesive (clayey) and non-cohesive (sandy) soils, the Terzaghi bearing capacity equation is given by:

$q_{ult} = cN_cF_c + qN_qF_q + 0.5\gamma BN\gamma F\gamma$[1]

q_{ult} = is the ultimate bearing capacity of the soil
c = is the cohesion of the soil,
$N_c, N_q, N\gamma$ = are bearing capacity factors obtained from bearing capacity charts or tables based on the type of soil.
σ'_{v0} = is the effective vertical stress at the base of the foundation
γ'_{sat} = is the effective saturated unit weight of the soil.

$$\gamma'_{sat} = \gamma_{sat} - \gamma_w$$

Where:

γ_{sat} = saturated unit weight of the soil
γ_W = unit weight of water
B = is the width of the foundation,
F_c, F_q, F_γ = is a shape factor.
The effective vertical stress σ'_{v0} is calculated as:

$$\sigma'_{v0} = \sigma_{v0} - \sigma_p$$

Where:

σ_{v0} = is the total overburden stress at the depth of the foundation,
σ_P = is the pore water pressure at the depth of the foundation.

Unit: (Pa) or (N/m²)

[1] This equation provides an estimate of the ultimate bearing capacity. It's important to note that additional factors, such as footing shape, depth, and soil layering, may influence the calculation. For more accurate and site-specific calculations, consulting with a geotechnical engineer is recommended

3.1.8. Consistency

Assess the soil consistency, which describes its state (e.g., liquid, plastic, or solid) under different moisture conditions. This helps in understanding how the soil behaves. In the context of soil mechanics, "consistency" refers to the relative ease with which a soil can be deformed or changed in shape. It is particularly associated with fine-grained soils such as clays and silts. Consistency is often expressed using the Atterberg Limits. These Atterberg Limits are useful in classifying fine-grained soils and understanding their engineering properties. The consistency of a soil can be described based on its position in the Unified Soil Classification System (USCS), where soils are categorized as silt, clay, or organic soil.

Consistency is often expressed using the Atterberg Limits.
Atterberg Limits, which include the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI).

3.1.8.1. Liquid Limit (LL):
The Liquid Limit is the moisture content at which a soil changes from a plastic to a liquid state during standardized testing. It is expressed as a percentage.

$$LL = \frac{Weight\ of\ soil\ at\ Liquid\ state}{Weight\ of\ Dry\ soil}\ x\ 100$$

3.1.8.2. Plastic Limit (PL):
The Plastic Limit is the moisture content at which a soil changes from a semi-solid to a plastic state during standardized testing. It is also expressed as a percentage.

$$PL = \frac{Weight\ of\ soil\ atPlastic\ state}{Weight\ of\ dry\ soil}\ x\ 100$$

3.1.8.3. Plasticity Index (PI):
The Plasticity Index is the difference between the Liquid Limit and Plastic Limit and provides a measure of the range of moisture content within which the soil exhibits plastic behavior.

PI = LL – PL

Unit: %[2]

[2] The units for consistency parameters (Liquid Limit, Plastic Limit, and Plasticity Index) are percentages (%). There is no specific unit for consistency itself, as it is a qualitative measure

3.1.9. Liquidity Index

Determine the liquidity index, which indicates whether the soil is in a liquid, plastic, or solid state. This is crucial for understanding the potential for settlement. The Liquidity Index (LI) is a parameter used in geotechnical engineering to express the liquidity or fluidity of a soil. It is often associated with fine-grained soils and is calculated using the Atterberg Limits, specifically the Liquid Limit (LL) and the Plastic Limit (PL). The Liquidity Index provides insights into the behavior of fine-grained soils and is often used in soil classification systems, such as the Unified Soil Classification System (USCS). The Liquidity Index helps engineers assess the consistency and plasticity of soils and is valuable in understanding their engineering properties. The Liquidity Index itself is dimensionless, as it is derived from the ratio of two percentage values. It is used to categorize soils as either cohesive or non-cohesive and aids in making decisions related to engineering and construction projects.

A dimensionless parameter indicating the relative fluidity or liquidity of a soil.

$$LI = \frac{Liquid\ limit\ (LL) - Plastic\ limit\ (PL)}{Plasticity\ Index\ (PI)}$$

Unit: %

3.1.10. pH and Chemical Composition

Evaluate the pH and chemical composition of the soil, as certain chemicals can impact soil stability and affect the corrosion of foundation materials. These parameters are typically assessed through soil testing and laboratory analysis. A geotechnical engineer can conduct these tests and provide a comprehensive soil report that informs foundation design and construction considerations. Understanding these soil parameters helps in

derived from these percentages. The Atterberg Limits are determined through laboratory testing, and the results aid in characterizing and classifying soils for engineering purposes.

selecting appropriate foundation types, reinforcement methods, and construction techniques to ensure the stability of a building's foundation.

Chemical composition refers to the types and proportions of chemical elements or compounds present in a substance. Let's address each one separately:

pH (Potential of Hydrogen):

pH is dimensionless. The scale represents the negative logarithm of the hydrogen ion concentration in moles per liter (mol/L or M).

Chemical Composition:

Chemical composition is expressed in terms of the percentage by weight of each element or compound in the sample. For example, the percentage of silicon, aluminum, iron, etc., in a soil sample.

Understanding pH and chemical composition is crucial in soil science and geotechnical engineering. pH influences soil properties, nutrient availability, and microbial activity. Chemical composition provides insights into soil mineralogy and potential reactivity, particularly in the context of expansive soils or soils prone to chemical reactions.

3.2. Water Management

Control water infiltration and accumulation around the foundation. Poor drainage, waterlogged soil, or excessive moisture can lead to soil erosion, compromising the foundation's stability.

3.2.1. Porosity

Porosity, which is measured as a percentage, is the amount of vacant space in rock or soil. It establishes how much water the land can hold in reserve. While low porosity soils have a restricted ability to store water, high porosity soils have the ability to hold more water.

Calculate the Total Volume (V_{total}): This represents the sample of rock or soil's total volume. Various techniques can be used to measure this, depending on the size and shape of the sample. You might apply methods like water displacement or geometric approximations for samples with unusual shapes.

Measure the Volume of Solids (V_{solid}): The volume that the solid particles in the rock or soil occupy is known as the Volume of Solids (V_{solid}). This measurement can be obtained by first weighing the sample and then using methods like displacement with a known fluid or geometric calculations to determine its volume.

Measure the Volume of Pore space ($V_{porespace}$): Understanding a material's porosity requires an understanding of its pore space, particularly in the context of water management where the transport and storage of water inside porous media are important. The number of voids or empty spaces that allow water to live within a substance is represented by the volume of pore space.

$V_t = V_s + V_p$

Using the following formula, you may determine porosity after you know all three measurements:

$P^3{}_t = \frac{V_p}{V_t}$

Unit: %

3.2.2. Permeability

Water permeability is the degree to which soil or rock can absorb and hold onto water. It is dependent upon variables like pore connectivity, packing configuration, and particle size. Water can move more swiftly via high permeability soils than through low permeability soils. Depending on the substance being evaluated, different laboratory experiments can be performed to measure permeability. Here are two such techniques:

- Constant Head Permeameter Test: This test measures the water flow rate through a specimen (such as a soil sample) while maintaining a constant head of water on one side of the specimen. Darcy's law can be used to calculate the specimen's permeability by measuring the flow rate.

- Falling Head Permeameter Test: This test employs a falling head scenario to allow water to pass through the specimen. The rate of change in the water level is monitored, and Darcy's law is used to determine the permeability. Typically, these tests are carried out in lab settings with specialized tools to guarantee precise readings and controlled environments. The type of material being tested, the anticipated permeability range, and the equipment available all influence the test method selection. To ascertain the permeability of natural materials in their natural habitat, in situ testing can also be carried out. These tests frequently use methods like slug tests, pumping tests in wells or boreholes, and geophysical permeability testing.

[3] The Symbol of porosity could be determined with (n or Ø)

The ability of a material to permit fluids, like water, to pass through it when subjected to a hydraulic gradient, a pressure difference, is known as its permeability. Typically, the coefficient k is used to express it. The following is the expression of Darcy's law, which is frequently used to explain fluid flow through porous media. The negative sign implies that flow happens in the direction of decreasing hydraulic head.

$Q = -KA.(h_1 - h_2)/L$

Where:

Q = is the volumetric flow rate (volume of fluid passing through a unit area per unite time)
k = is the permeability of the material
A = is the cross-sectional area through which the fluid flows.
$\Delta h = (h1 - h2)$ is the hydraulic head difference (pressure gradient)
L = is the length of the flow path.

Unit: (m/s)[4]

3.2.3. Hydraulic conductivity

is a measurable property that indicates how well a soil can transfer water. It measures the speed at which water can move under a hydraulic gradient across a unit cross-sectional area of soil. It is affected by the fluid's viscosity as well as permeability.

One way to solve for hydraulic conductivity k is to rearrange the formula:

$$k = -\frac{Q}{A}\frac{dl}{dh}$$

Unit: (m/s)[5]

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[4] The unit could be (mm/s) or in American unit is (in/s) or (ft/day)

[5] The unit could be differ depending on the units used for flow rate, area, and distance, it can be stated in either feet per day (ft/day) or inches per second (in/s) in the US customary units.

3.2.4. Saturated Hydraulic Conductivity

The rate at which water moves through saturated soil is referred to as saturated hydraulic conductivity. Knowing how rapidly water can seep into the soil and impact surface runoff or groundwater recharge is crucial.

$$\mathrm{q(x)} = -\mathrm{K(x)}\nabla\mathrm{h}\ \mathrm{(x)}$$

That represent by this formula:
Where:
x = is a vector of space coordinates
q = is a seepage velocity vector
h = is hydraulic head
K = is the hydraulic conductivity tensor

Unit: ($m^3/m^2.s$) = (m/s)

3.2.5. Capillary Action

Water's capacity to rise against gravity in small areas, like the pore spaces between soil particles, is known as capillary action. It can impact moisture distribution, plant root uptake, and water retention and movement in unsaturated soils.

The capillary force between two particles:

$$F = -2\pi\sigma Q_1 Q_2 q K_1 q L_1 + O q^2 R_k^2 r_k < L$$

where σ is the liquid–fluid interfacial tension, r1 and r2 are the radii of the two contact lines and, is the 'capillary charge' of the particle

$$Q_i = r_i \sin ¥_i \ (i = 1{,}2)$$

In addition:

$$q^2 = \Delta\rho g/\sigma(inthickfilm)$$

$$q^2 = \Delta\rho g - ¶'/\sigma(inthickfilm)$$

Here Δρ is the difference between the mass densities of the two fluids and Π′ is the derivative of the disjoining pressure with respect to the film thickness.

Symbol of coefficient: **(**ΔW)

Unit: (Pa) or (N/m^2)

3.2.6. Infiltration Rate

The pace at which water percolates through the surface of the soil is known as the infiltration rate. It is influenced by both internal and external variables, such as soil moisture levels and rainfall intensity, as well as soil characteristics including texture, structure, and organic matter concentration.

$f = K_s + K_s M_d S_f / F$

where f is the infiltration rate, F is accumulative infiltration, Kg is the hydraulic conductivity of the transmission zone, M_d is the difference between final and initial volumetric water contents ($M_d = e_o - e_i$), and Sf is the effective suction at the wetting front. For a given soil with a given initial water content equation 4 may be written as,

$f = A/F + B$

where A and B are parameters that depend on the soil properties, initial water content and distribution, and surface conditions such as cover, crusting, etc.

Symbol of coefficient: **(**f) or (l)

Unit: (in/h) or (mm/h)

3.2.7. Soil Moisture Content

The amount of water in the soil, measured as a percentage of the dry weight of the soil, is known as the soil moisture content. It is a crucial metric for evaluating the possibility for soil erosion, slope stability, plant water availability, and soil water storage.

$$volumetric\ moisture\ content\ (\theta) = \frac{volume\ of\ water\ in\ the\ soil}{Total\ volume\ of\ soil}$$

Symbol of coefficient: **($\boldsymbol{\theta}$)**

Unit: (cm^3) or (litr)

3.2.8. Drainage Characteristics

The ability of soil to eliminate surplus water through natural or man-made drainage channels is referred to as drainage characteristics. Controlling waterlogging, reducing the chance of floods, and preserving the stability of structures erected on or inside the soil all depend on an understanding of drainage characteristics.

3.2.8.1. Permeability

$$k = \frac{Q.L}{A.\Delta h.t}$$

k = Permeability (m/s) or (cm/s)
Q = Volume of water (m^3) or (cm^3)
L = Length of the soil column (m) or (cm)
A = cross-section area of the soil sample (m^2) or (cm^2)
Δh = Head difference (m) or (cm)
t = Time (s)

3.2.8.2. Hydraulic Conductivity

$$K = k.\frac{\rho g}{\mu}$$

K = Hydraulic Conductivity (m/s)
k = Permeability (m/s)
ρ = Density of water (kg/m^3)
g = Gravitational acceleration (9.81 m/s^2)
μ = Dynamic viscosity of water (Pa.s) or ($N.s/m^2$)

3.2.8.3. Infiltration Rate

$$I = \frac{V}{A.t}$$

I = Infiltration Rate (mm/h) or (cm/h)
V = Volume of water infiltrated (mm) or (cm)
A = Area of infiltration (m^2) or (cm^2)
t = Time (h)

3.2.8.4. Surface Runoff

$$R = P - F$$

R = Surface Runoff (mm or cm)
P = Precipitation (mm or cm)
F = Infiltration or losses (mm or cm)

3.2.8.5. Drainage time

$$t_d = \frac{V}{Q}$$

t_d = Drainage time
V = Volume of water or drain (m^3 or liters)
Q = Flow rate (m^3/s or liters/s)

3.2.8.6. Porosity

$$n = \frac{V_v}{V_t}$$

n = Porosity (dimensionless, expressed as a percentage)
V_v = Volume of voids (m^3)
V_t = Total volume of sample (m^3)

3.2.8.7. Drainage coefficient

$$D_c = \frac{Q}{A}$$

D_c = Drainage coefficient (mm/day)
Q = Discharge rate (mm/day)
A = Area (m^2)

3.2.8.8. Saturated Hydraulic conductivity

$$K_{sat} = \frac{Q.L}{A.\Delta h.t}$$

K_{sat} = Saturated Hydraulic conductivity (m/s or cm/s)
Q = Volume of water (m^3 or cm^3)
L = Length of the soil sample (m or cm)
A = Cross-section area of the soil sample (m^2 or cm^2)
Δh = Hydraulic head difference (m)
t = Time (s)

3.3. Foundation Integrity

Regularly inspect and address any damage to the foundation, including cracks, settlement, or deterioration. Repair and reinforce the foundation as needed to maintain its structural integrity.

Foundation integrity refers to the stability and soundness of a building's foundation, which supports the entire structure. Assessing the integrity of a foundation involves evaluating various parameters related to its performance, stability, and the soil conditions surrounding it. Below are key parameters and formulas related to foundation integrity.

3.3.1. Bearing Capacity of Soil

The ability of the soil to support the loads applied by the foundation.

$$q_u = cN_c + \sigma' N_q + 0.5\gamma B N\gamma$$

q_u = Ultimate bearing capacity[6] (kPa)
c = Cohesion of soil (kPa)
σ′ = Effective overburden pressure (kPa)
γ = Unit weight of soil (kN/m^3)
B = Width of foundation (m)
N_c, N_q, N_γ = Bearing capacity factors (depending on soil type and angle of internal friction)

3.3.2. Settlement

The amount of vertical displacement or settlement of the foundation due to the loads applied on the soil.

$$S_c = \frac{C_c H_0}{1 + e_0} \log\left(\frac{\sigma' + \Delta\sigma'}{\sigma'}\right)$$

S_c = Consolidation settlement (m)
C_c = compression index

[6] Considering: The allowable bearing capacity is calculated by dividing the ultimate bearing capacity by a factor of safety (FS)

H_0 = initial thickness of the compressible layer (m)
e_0 = Initial void ratio
σ' = Initial effective stress (kPa)
$\Delta\sigma'$ = Increase in effective stress due to applied loads (kPa)

3.3.3. Differential Settlement

The uneven settlement of the foundation that can lead to structural distortion. Maintain uniform soil properties and proper load distribution to avoid differential settlement.

3.3.4. Foundation Depth

The depth at which the foundation is placed to ensure stability against shear failure and avoid excessive settlement. Depth is often chosen based on local soil conditions, frost depth, and groundwater level. The general rule is that the foundation depth should be at least as deep as the frost line to avoid freezing and thawing issues.

3.3.5. Sliding Resistance

The ability of the foundation to resist sliding due to horizontal forces such as wind or seismic loads.

$$R_s = \mu W$$

R_s = Sliding resistance (kN)
μ = Coefficient of friction between the foundation and soil
W = Weight of the structure (kN)

3.3.6. Overturning Stability

The ability of the foundation to resist overturning moments caused by lateral forces.

$$M_{resist} = W.d$$

M_{resist} = Moment resisting overturning (kN-m)
W = weight of the structure(kN)

d = Distance from the center of gravity of the structure to the edge of the foundation (m)

3.3.7. Lateral Earth Pressure

The pressure exerted by soil on retaining walls or other foundation structures.

$$P_a = 0.5\gamma\, H^2\, K_a$$

P_a = Active earth pressure (kN/m^2)
γ = Unit weight of soil (kN/m^3)
H = Height of the retaining structure (m)
K_a = Coefficient of active earth pressure, dependent on soil properties and internal friction angle (Ø)

3.3.8. Soil-Structure Interaction (SSI)

Interaction between the soil and the structure, which influences both the soil response and structural performance. Models like Winkler springs or finite element methods are used to analyze SSI.

3.3.9. Buoyancy[7]

The upward buoyant force acting on the foundation due to groundwater.

$$F_b = \gamma_{water} V_{displaced}$$

F_b = Buoyant force (kN)
γ_{water} = Unit weight of water (9.81 kN/m^3)
$V_{displaced}$ = Volume of water displaced by the foundation (m^3)

[7] for foundations below the water table

3.3.10. Soil Bearing Capacity under Water[8]

The bearing capacity of soil when submerged in water.

$$\sigma' = \sigma - u$$

σ' = Effective stress (kPa)
σ = Total stress (kPa)
u = Pore water pressure (kPa)

[8] Submerged Condition

3.4. Underpinning

Consider underpinning if the foundation needs additional support or if there are signs of settlement. This involves strengthening the foundation by extending its depth or providing supplementary support.

Underpinning is a method used to strengthen and stabilize the foundations of existing structures. When performing underpinning, several key parameters must be considered to ensure the safety and effectiveness of the process. Here's a list of the main parameters to calculate and evaluate.

3.4.1. Load Bearing Capacity of Existing Foundation

The ability of the existing foundation to support the loads applied to it (from the structure and any new additions).

$$\text{Bearing Capacity} = \frac{P}{A_f}$$

q = Bearing capacity of soil (kN/m^2)
P = Load from the structure (kN or tons)
A_f = Foundation area (m^2)

3.4.2. Depth of New Foundation (Depth to Stable Stratum)

The depth at which a stable and strong soil layer is found for transferring the load safely from the foundation The new foundation depth should reach a stable stratum that can bear the load without excessive settlement.[9]

[9] Key parameters:
Depth of the existing foundation (Df) (in meter)
Depth of the stable soil layer (Ds) (in metere)

3.4.3. Settlement Calculation

The downward movement of the foundation under the applied loads. Controlling settlement is critical for maintaining the structural integrity of the building.

$$S = \frac{P}{C_s A_f}$$

S = Settlement Calculation (mm)
P = Applied load (kN)
Cs = Soil compressibility (kN/m²)
A_f = Foundation area (m²)

3.4.4. Bearing Capacity of New Foundation

The capacity of the new underpinning foundation to support both the existing and any additional loads.

$$P = q \cdot A_n$$

P = [Load], New Bearing Capacity (kN)
q = Soil bearing capacity (kN/m²)
A_n = Area of the new underpinning foundation (m²)

3.4.5. Lateral Earth Pressure

The pressure exerted by the soil horizontally against the foundation walls, which is important when underpinning to prevent lateral movement or collapse.

$$\text{Lateral Pressure} = K \cdot \gamma \cdot h$$

Lateral Pressure = (kN/m²)
γ = Soil unit weight (kN/m³)
h = Foundation depth (m)
K = Coefficient of lateral earth pressure (dimensionless, dependent on soil type)

3.4.6. Soil Bearing Capacity of Underpinning System

The strength of the soil beneath the new underpinning elements (like piles or piers) to support the structure.

$$q = c + \gamma D_f \cdot Nq$$[10]

c = Cohesion of soil (kN/m²)
ϕ = Angle of internal friction (degrees)
D_f = Depth of the foundation (m)
N_q = Bearing capacity factor

3.4.7. Shear Strength of Soil

The maximum stress the soil can handle before failure occurs.

$$\tau = c + \sigma \cdot \tan(\phi)$$

τ = Shear strength of soil (kN/m²)
c = Soil cohesion (kN/m²)
σ = Normal stress (kN/m²)
ϕ = Angle of internal friction (degrees)

3.4.8. Moment and Shear in Existing and New Foundation

The structural response to the loads applied to both the existing and the new underpinning foundations, including bending moments and shear forces.

M = Moment (kNm)
V = Shear (kN)
L = Length of foundation element (m)

[10] for shallow foundations, depending on soil type

3.4.9. Differential Settlement

Uneven settlement between different sections of the foundation, which can lead to cracking or structural issues.

$$\text{Differential Settlement} = \frac{|S_1 - S_2|}{L}$$

S_1, S_2 = Settlement at different points (mm)
L = Distance between points (m)

3.4.10. Safety Factor

A factor of safety to ensure the foundation's capacity exceeds the applied loads.

$$F_s = \frac{q_u}{P}$$

P = Design load (kN)
q_u = Ultimate bearing capacity(kN/m^2)

3.5. Grading

Ensure proper grading around the building to direct water away from the foundation. Proper slope and grading prevent water from pooling around the structure, minimizing the risk of soil erosion. In the context of controlling stability, grading refers to the classification of soil or aggregate materials based on the particle size distribution, often determined through a sieve analysis. Grading plays a significant role in soil stability as it affects the soil's drainage, compaction, shear strength, and load-bearing capacity, all of which are crucial for ensuring the stability of a foundation or structure.

3.5.1. Particle Size Distribution

Grading is classified as well-graded or poorly graded: Well-graded soil: Has a wide range of particle sizes, creating a denser, more stable soil structure with fewer voids, which enhances stability.

Poorly graded soil: Consists of mostly similar-sized particles, leading to more voids and lower stability

3.5.2. Compaction and Density

Well-graded soils can be compacted more easily, increasing their density and strength, which reduces settlement and improves load-bearing capacity. Poorly graded soils are more difficult to compact effectively, resulting in lower stability.

3.5.3. Drainage Characteristics

Grading affects permeability, with finer soils tending to retain water and coarser soils allowing for better drainage. Well-graded soils often provide a balance, offering moderate drainage and stability, while controlling moisture levels that could impact soil strength.

3.5.4. Shear Strength

Proper grading improves shear strength, reducing the risk of slope failure or foundation slippage, especially in sandy or loose soils.

3.6. Drainage Systems

Implement effective drainage systems, including gutters, downspouts, and French drains, to manage rainwater and prevent it from causing soil instability or water damage to the foundation. For designing and evaluating an effective drainage system, several key parameters need to be considered to ensure proper water management, soil stability, and structural safety. Here are the primary parameters:

By evaluating these parameters, engineers can design an efficient drainage system that minimizes flooding, erosion, and soil instability while ensuring effective water management.

3.6.1. Soil Permeability

The ability of soil to allow water to pass through it. High permeability allows water to drain quickly, while low permeability can cause water to pool and lead to instability.

$$K = \frac{Q.L}{A.H}$$

K = Hydraulic conductivity (cm/s or m/day)
Q = Flow rate of water (m^3/s or L/s)
L = Length of soil sample (m or cm)
A = Cross-sectional area of soil sample (m^2 or cm^2)
H = Hydraulic head difference (m or cm)

3.6.2. Soil Saturation Level

The degree to which soil pores are filled with water. Soil with high saturation levels may not drain effectively, increasing the risk of soil erosion and structural instability.

3.6.3. Drainage Slope

The angle or gradient of the surface designed to direct water flow. A properly sloped drainage system channels water away from structures, reducing water buildup and soil erosion.

$$S = \frac{\Delta h}{L}.100$$

S = Slope (as a percentage, %)
Δh = Vertical change in elevation (m or cm)
L = Horizontal distance over which the change occurs (m or cm)

3.6.4. Hydraulic Conductivity

The ease with which water can move through pore spaces or fractures in soil or rock. Higher hydraulic conductivity indicates faster drainage and is crucial for designing effective drainage in different soil types.

3.6.5. Runoff Coefficient

A factor that represents the portion of rainfall that will runoff rather than infiltrate. High runoff can lead to flooding or erosion, especially on impermeable surfaces or compacted soils.

$$Q = C \times I \times A$$

Q = Runoff volume (m^3/s or L/s)
C = Runoff coefficient (unitless, between 0 and 1)
I = Rainfall intensity (mm/h or in/h)
A = Catchment area (m^2 or hectares)

3.6.6. Infiltration Rate

The rate at which water enters the soil from the surface. Low infiltration rates can lead to surface water buildup, necessitating enhanced drainage systems.

$$f_t = f_c + (f_0 - f_c)\, e^{-kt}$$

f_t = Infiltration rate at time t (m/hr or cm/h)
f_0 = Initial infiltration rate (mm/hr)
f_c = Steady infiltration rate (mm/hr)
k = Decay constant (1/hr)
t = Time (hr)

3.6.7. Groundwater Table Level

The depth at which the soil is fully saturated with water. High water tables can increase soil moisture content, causing inadequate drainage and requiring adjustments in system design.

Catchment Area

The area from which water flows into a particular drainage point. A larger catchment area may require a more robust drainage system to handle increased water volume.

3.6.8. Surface Roughness[11]

The texture of the land surface, which affects water flow. Rougher surfaces slow down water flow, reducing erosion but potentially requiring design adjustments for effective drainage.

$$Q = \frac{1}{n} AR^{2/3}S^{1/2}$$

Q = surface roughness (m^3/s)
n =Manning's roughness coefficient (dimensionless)
A = Cross-sectional area of flow (m^2)
R = Hydraulic radius (area of flow divided by wetted perimeter, m)
S = Slope of the channel (m/m)

3.6.9. Rainfall Intensity and Duration

The rate of rainfall over time. High-intensity storms can overwhelm drainage systems if they aren't designed to handle peak flows.

$$I = \frac{P}{t}$$

I = Rainfall Intensity (mm/h or in/h)

[11] Manning's Equation for Channel Flow

P = Total precipitation (mm)
t = Duration of rainfall (h)

3.6.10. Pipe/Channel Size and Capacity

The diameter and maximum water capacity of pipes or channels used in the drainage system. Properly sized pipes and channels are essential to prevent water buildup and flooding.

3.6.11. Soil Erodibility

The susceptibility of soil to erosion by water flow. Erodible soils require additional drainage features to prevent sediment buildup and system clogging.

3.7. Monitoring Systems

Install monitoring systems to track any movement or settling of the foundation. These systems can provide early warnings, allowing for prompt intervention before significant issues arise.

3.7.1. Deformation and Displacement

Monitoring horizontal and vertical displacements provides insights into potential settlement, heave, or lateral shifts.

$$\Delta d = d_{final} - d_{initial}$$

Δd = Displacement (mm or cm)
dfinal = Final position (mm or cm)
dinitial = Initial position (mm or cm)

3.7.2. Settlement Rate

Excessive or uneven settlement rates can lead to structural distortion or instability.

$$SR = \frac{\Delta S}{\Delta t}$$

SR = Settlement Rate (mm/day or mm/year)
ΔS = Change in settlement (mm)

Δt = Time interval (days or years)

3.7.3. Tilt or Rotation Angle

Tilt monitoring is crucial in high-rise buildings, retaining walls, and slopes where stability is affected by minor angular shifts.

Calculation: Measures the angular shift in a structure to assess its inclination or potential for overturning.

$$\theta = \tan^{-1}\left(\frac{\Delta \mathrm{h}}{\mathrm{L}}\right)$$

θ = angle of displacement (radians or degrees)
Δh = Vertical displacement (mm or cm)
L = Horizontal distance over which the displacement occurs (mm or cm)

3.7.4. Stress and Strain in Materials

High stress and strain levels over time can signal structural weakening or damage.

Calculation: Used to monitor the stress and strain experienced by structural components over time, which indicates material fatigue or failure risk.

Stress:

$$\sigma = \frac{F}{A}$$

σ = Stress (Pa or N/m^2)
F = Forced applied
A = Cross-sectional area

Strain:

$$\varepsilon = \frac{\Delta L}{L_0}$$

ε = Strain (dimensionless)
ΔL = change in length
L_0 = original length

3.7.5. Groundwater Pressure (Pore Water Pressure)

High pour water pressure can lead to soil liquefaction or instability, especially in clayey or saturated soils.

Calculation: Monitoring pore water pressure helps in assessing the water content in the soil, which affects soil stability.

$$u = \gamma_w . h$$

u= pore water pressure (kPa or kN/m^2)

γ_w = unit weight of water (9.81 kN/m^3)

h = depth of water table (m)

3.7.6. Factor of Safety (FOS)

A FOS less than 1 indicates potential instability. Monitoring changes in FOS over time helps detect risks early.

Calculation: FOS is calculated to assess the stability and load-bearing capacity of a structure or slope.

$$\text{FoS} = \frac{c+(\sigma - u)tan\emptyset}{\tau}$$

c = cohesion (kPa or kN/m^2)
σ = normal stress (kPa or kN/m^2)
u = pore water pressure (kPa or kN/m^2)
ϕ = internal friction angle (radians or degrees)
τ = applied shear stress (kPa or kN/m^2)

3.7.7. Vibration Monitoring

Excessive vibrations can lead to material fatigue and structural instability, especially in foundations near construction sites or heavy traffic areas.

Calculation: Measures the frequency, amplitude, and acceleration of vibrations, which can affect structural stability.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

f_n= natural frequency (Hz) or (S^{-1})[12]
k = stiffness of the structure (N/m) or (kN/m)
m = mass of the structure (kg)

3.7.8. Crack Width Monitoring

Monitoring crack width helps in assessing potential progressive structural damage or movement.

Calculation: Measures the width change of cracks over time to evaluate structural integrity.

$$\Delta w = w_f - w_i$$

Δw = change in crack width (mm or in)
w_f = final crack width (mm or in)
w_i= initial crack width (mm or in)

[12] cycles per second

3.8. Waterproofing

Apply waterproofing measures to protect the foundation from water infiltration. This is especially important for basements and below-grade structures.

3.9. Vegetation Control

Manage vegetation around the building, as tree roots can potentially affect the foundation by extracting moisture from the soil or causing physical damage through growth.

3.10. Seismic Considerations

Assess the seismic risk in the area and consider seismic retrofitting measures if necessary. This may involve reinforcing the foundation to enhance its resistance to earthquake forces.

3.11. Professional Inspections

Regularly engage professional engineers to conduct structural assessments and inspections. They can identify potential issues early on and recommend appropriate control measures.

Chapter 4

4. Vulnerability Assessment

The pathology of old buildings is a process that identifies, analyzes and provides appropriate solutions to the problems and deficiencies in these buildings. The main objective of this process is to preserve and restore the cultural and historical heritage by respecting the principles of restoration and maintenance.

The seismic vulnerability of a building depends on the lack of some basic features that may affect the essential structural components. These deficiencies are the result of various reasons such as age, poor maintenance, old design, material specifications, construction site and natural events. The current Italian standard recommends that the seismic vulnerability assessment of existing buildings should be carried out, as far as possible, in relation to the design guidelines.

4.1. Factors affecting damage to old buildings

4.1.1. Natural factors

<u>Earthquakes:</u> cause cracks and destruction of old structures.

<u>Floods</u>: Water penetration into the foundation and walls, leading to structural weakening.

<u>Environmental erosion:</u> the effect of wind, rain and temperature changes on building materials.

4.1.2. Human factors

<u>Inappropriate change of use:</u> Uses that are not compatible with the structure of the building that damage it.

<u>Lack of timely maintenance and repair</u>: Neglect of required repairs that lead to aggravation of damage.

<u>Unprincipled interventions:</u> Repairs and changes without observing repair standards that damage the structure of the building.

4.2. Types of structural damage in old buildings

4.2.1. Cracks

Vertical cracks: caused by uneven settlement of the foundation

Horizontal cracks: usually due to lateral pressure of the soil on the basement walls

Oblique cracks: due to shear forces and lateral displacement caused by earthquakes

4.2.2. Wear and tear of materials

Old brickwork: causing scaling, cracking, and reduced mortar adhesion
Concrete: carbonation of concrete, rusting of rebar, and surface peeling

4.2.3. Building foundation instability

Foundation settlement and displacement: Weakness in the foundation system and changes in soil moisture

Frost heave: In cold regions, freezing water under the foundation causes movement and cracking

4.3. Pathology stages of old buildings

4.3.1. Inspection and documentation

- Preparation of existing maps and documentation of the building.
- Photography and recording of the current condition.
-

4.3.2. Identification of damage

- Inspection of cracks, settlements and deformations.
- Identification of structural and non-structural weaknesses.

4.4. Analysis and evaluation

- Investigation of the causes of damage.
- Evaluation of the level of risk and prioritization of repairs.

4.5. Providing restoration solutions

- Development of a restoration plan according to scientific and technical principles.
- Using materials and techniques compatible with the original structure of the building.
-

4.6. Structural Typology and Its Role in Identifying Seismic Vulnerability

Structural Typology is one of the most important tools in assessing seismic vulnerability. Understanding the type of structure, its material properties, and its implementation helps predict the behavior of a building against an earthquake. This information allows engineers to identify potential hazards and select appropriate strengthening methods.

4.6.1. The impact of typology on the vulnerability of buildings
Identifying weaknesses based on the type of structure
Each type of structure has its own characteristics, and some of them are more vulnerable to earthquakes. The following table shows some of the most important types of structures and their weaknesses:

Type of Structure	Characteristics	Weaknesses Against Earthquakes
Masonry Structures	Load-bearing walls made of brick or stone	Heavy weight, low ductility, shear failure in walls
Reinforced Concrete (RC) Structures	Reinforced concrete frames with beams and columns	Weakness in connections, shear failure of columns, beam-column joint failure
Steel Structures	Steel frame with welded or bolted connections	Brittle fracture in welds, buckling instability in slender members
Timber Structures	Wooden frame buildings	Low resistance to shear forces, susceptibility to moisture and insect damage
Composite Structures	Combination of concrete and steel or wood and steel	Design and construction challenges, need for precise connections

Figure 10. Typology on the vulnerability

4.6.2. The impact of structure type on failure methods in earthquakes
Structure typology directly affects the failure pattern in earthquakes. Some of the most important failure patterns are:

- Shear failure in masonry walls: diagonal cracks at corners and sudden failure of walls.

- Connection failure in concrete structures: beam-column instability and collapse of floors.
- Buckling of steel columns: severe deformations and structural failure.
- Pounding effect: adjacent buildings colliding with each other in an earthquake.

4.7. Application of typology in damage identification

4.7.1. Masonry structures

Common problems: cracking of walls, separation of materials, weak connection of walls.

4.7.2. Reinforced concrete structures

Common problems: weak ductility, shear failure, destruction of columns.

4.7.3. Steel structures

Common problems: failure of connections, weak stability against lateral forces.

Chapter 5

5. A BIM methodology to calculate the risks assessment

5.1. Introduction

In this study, the BIM approach was used to assess seismic hazards in an old school building. This method allows for accurate 3D modeling, structural vulnerability assessment, and proposed retrofitting solutions. Due to the lack of access to the numerical model in SAP2000 software, the analyses were conducted based on valid standards such as Eurocode 8 and NTC 2018 and a review of previous studies.

Using BIM leads to risk management, while also identifying the time gap and the future of the project. Although this is done more traditionally, it also has other necessities, including ensuring safety in construction and reducing costs and time.
During the project, there is always a range of risks, so by using BIM we can reduce and control them.
However, it should be noted that we always face challenges, such as:

- Timely collection and analysis
- Knowledge and experience management
- Effective communication environment

Since people leave the project after it is completed, if things are not recorded correctly, a large amount of information may be lost.
In the meantime, for ease and coordination in the work, a series of rules, which we call “Automatic Rule Checking”, can be considered.
These models help engineers a lot. For example, they store all project elements in the form of IFC.
Although most efforts are focused on the design and construction phase, BIM can still be used in other phases such as facilities management or maintenance management.

5.2. BIM Methodology in Risk Assessment

In this study, BIM model in Revit is used to model the building. This model includes structural load-bearing components such as walls, beams, columns, slabs and the assumption of foundations. Then, the model information is extracted to assess the seismic vulnerability, as much as possible. In the absence of SAP2000 software, theoretical analyses based on valid standards and regional data are used to investigate the risks.

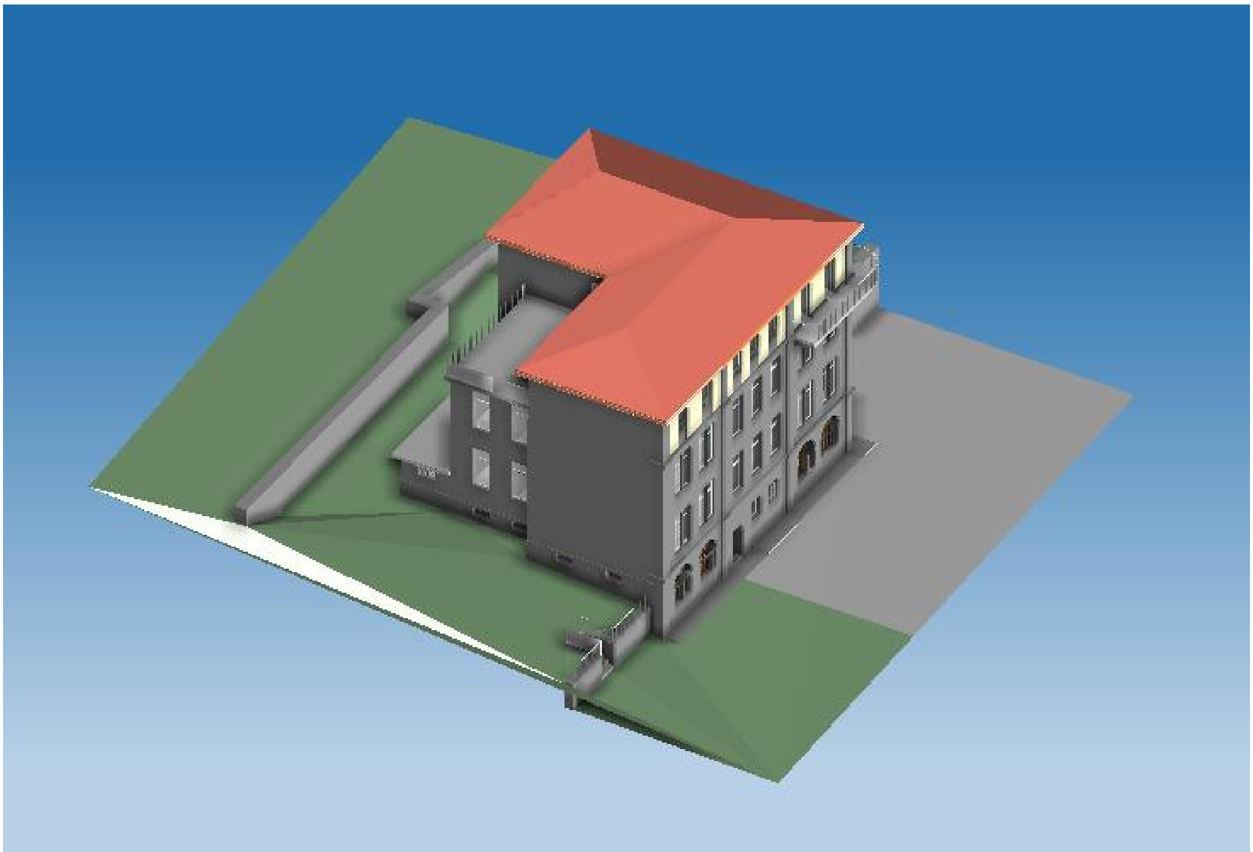

Figure 11. The Revit model 3D

This model was prepared using existing maps, along with surveying and mapping of the project site. A sample of the existing maps is provided below.

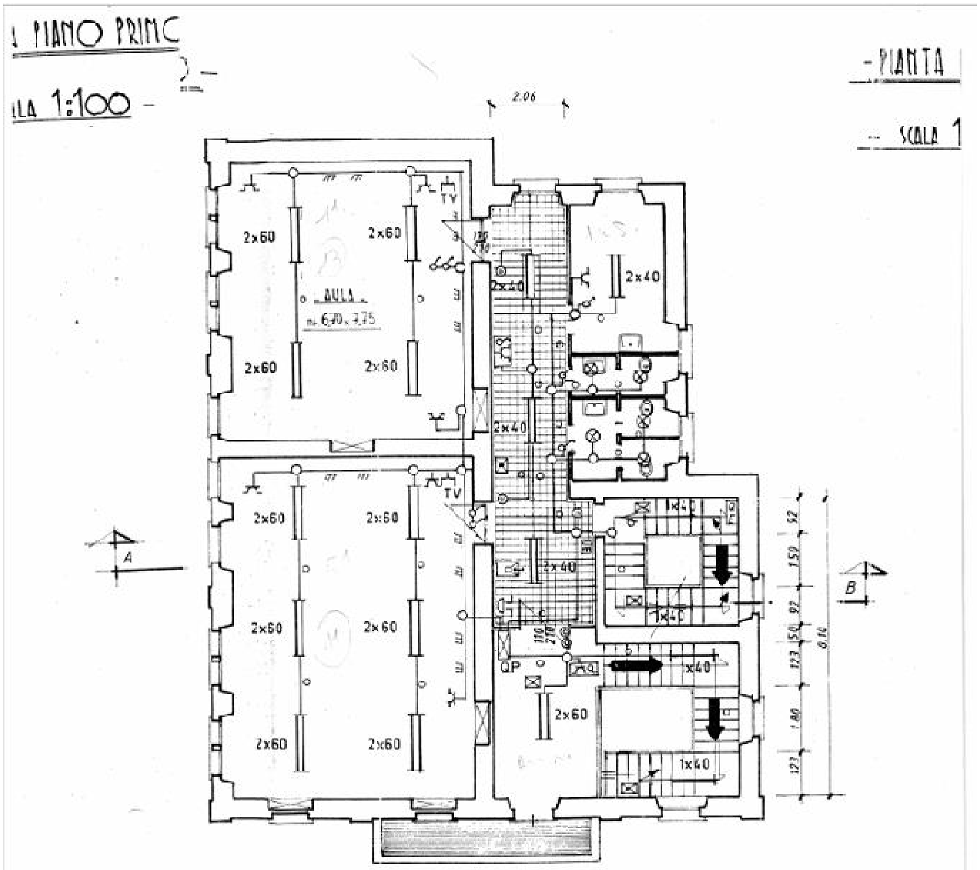

Figure 12. The first-floor plan

5.3. Structural Seismic Analysis (Manual and Experimental)

5.3.1 Seismic Loading According to NTC 2018

In the seismic design of buildings, according to NTC 2018, the earthquake force is applied to the structure as a horizontal load. For this building, the northern Italian region is considered, where, based on seismic hazard maps, the seismic design factor (ag/g) is about 0.25-0.3.

5.3.2. Determining the soil type and its effects and Seismic parameters in structural design

According to the geotechnical data of the region, the soil this building, in northern Italy is classified as B, which has a significant impact on increasing the structural behavior factor (q). This classification is determined based on the soil composition, density and bearing capacity.

Tab. 3.2.II – *Categorie di sottosuolo che permettono l'utilizzo dell'approccio semplificato.*

Categoria	Caratteristiche della superficie topografica
A	*Ammassi rocciosi affioranti o terreni molto rigidi* caratterizzati da valori di velocità delle onde di taglio superiori a 800 m/s, eventualmente comprendenti in superficie terreni di caratteristiche meccaniche più scadenti con spessore massimo pari a 3 m.
B	*Rocce tenere e depositi di terreni a grana grossa molto addensati o terreni a grana fina molto consistenti,* caratterizzati da un miglioramento delle proprietà meccaniche con la profondità e da valori di velocità equivalente compresi tra 360 m/s e 800 m/s.
C	*Depositi di terreni a grana grossa mediamente addensati o terreni a grana fina mediamente consistenti* con profondità del substrato superiori a 30 m, caratterizzati da un miglioramento delle proprietà meccaniche con la profondità e da valori di velocità equivalente compresi tra 180 m/s e 360 m/s.
D	*Depositi di terreni a grana grossa scarsamente addensati o di terreni a grana fina scarsamente consistenti,* con profondità del substrato superiori a 30 m, caratterizzati da un miglioramento delle proprietà meccaniche con la profondità e da valori di velocità equivalente compresi tra 100 e 180 m/s.
E	*Terreni con caratteristiche e valori di velocità equivalente riconducibili a quelle definite per le categorie C o D,* con profondità del substrato non superiore a 30 m.

Figure 13. The type of soil, according to standard of NTC 2018

Topographic effects occur due to the location of the building on hills or steep slopes.
If the building is on an uneven surface, the coefficients T1 to T4 can be used to take into account the effects of seismic resonance. In the case of the building in question, this coefficient is defined as T1.

Tab. 3.2.III – *Categorie topografiche*

Categoria	Caratteristiche della superficie topografica
T1	Superficie pianeggiante, pendii e rilievi isolati con inclinazione media $i \leq 15°$
T2	Pendii con inclinazione media $i > 15°$
T3	Rilievi con larghezza in cresta molto minore che alla base e inclinazione media $15° \leq i \leq 30°$
T4	Rilievi con larghezza in cresta molto minore che alla base e inclinazione media $i > 30°$

Figure 14. The category of topology, according to standard of NTC 2018

Definition of seismic response spectrum coefficients (Tc, Tb, Td). These coefficients are used to define the shape of the earthquake design spectrum. Their values depend on the soil type and seismic zone.
The recommended values according to NTC 2018 are given in the table below:

Tab. 3.2.VI - *Valori dei parametri dello spettro di risposta elastico della componente verticale*

Categoria di sottosuolo	S_S	T_B	T_C	T_D
A, B, C, D, E	1,0	0,05 s	0,15 s	1,0 s

Figure 15. The response spectrum coefficients, according to standard of NTC 2018

Other seismic parameters include the behavior coefficient, which, according to NTC 2018, can be considered equal to one for this structure.

Tab. 7.3.II – *Valori massimi del valore di base q_0 del fattore di comportamento allo SLV per diverse tecniche costruttive ed in funzione della tipologia strutturale e della classe di duttilità CD*

	q_0	
Tipologia strutturale	CD"A"	CD"B"
Costruzioni di calcestruzzo (§ 7.4.3.2)		
Strutture a telaio, a pareti accoppiate, miste (v. § 7.4.3.1)	4,5 α_u/α_1	3,0 α_u/α_1
Strutture a pareti non accoppiate (v. § 7.4.3.1)	4,0 α_u/α_1	3,0
Strutture deformabili torsionalmente (v. § 7.4.3.1)	3,0	2,0
Strutture a pendolo inverso (v. § 7.4.3.1)	2,0	1,5
Strutture a pendolo inverso intelaiate monopiano (v. § 7.4.3.1)	3,5	2,5
Costruzioni con struttura prefabbricata (§ 7.4.5.1)		
Strutture a pannelli	4,0 α_u/α_1	3,0
Strutture monolitiche a cella	3,0	2,0
Strutture con pilastri incastrati e orizzontamenti incernierati	3,5	2,5
Costruzioni d'acciaio (§ 7.5.2.2) e composte di acciaio-calcestruzzo (§ 7.6.2.2)		
Strutture intelaiate Strutture con controventi eccentrici	5,0 α_u/α_1	4,0
Strutture con controventi concentrici a diagonale tesa attiva Strutture con controventi concentrici a V	4,0 2,5	4,0 2,0
Strutture a mensola o a pendolo inverso	2,0 α_u/α_1	2,0
Strutture intelaiate con controventi concentrici	4,0 α_u/α_1	4,0
Strutture intelaiate con tamponature in murature	2,0	2,0
Costruzioni di legno (§ 7.7.3)		
Pannelli di parete a telaio leggero chiodati con diaframmi incollati, collegati mediante chiodi, viti e bulloni Strutture reticolari iperstatiche con giunti chiodati	3,0	2,0
Portali iperstatici con mezzi di unione a gambo cilindrico	4,0	2,5
Pannelli di parete a telaio leggero chiodati con diaframmi chiodati, collegati mediante chiodi, viti e bulloni.	5,0	3,0
Pannelli di tavole incollate a strati incrociati, collegati mediante chiodi, viti, bulloni Strutture reticolari con collegamenti a mezzo di chiodi, viti, bulloni o spinotti		2,5

Strutture cosiddette miste, con intelaiatura (sismo-resistente) in legno e tamponature non portanti		
Strutture isostatiche in genere, compresi portali isostatici con mezzi di unione a gambo cilindrico, e altre tipologie strutturali		1,5
Costruzioni di muratura (§ 7.8.1.3)		
Costruzioni di muratura ordinaria	$1{,}75\ \alpha_u/\alpha_1$	
Costruzioni di muratura armata	$2{,}5\ \alpha_u/\alpha_1$	
Costruzioni di muratura armata con progettazione in capacità	$3{,}0\ \alpha_u/\alpha_1$	
Costruzioni di muratura confinata	$2{,}0\ \alpha_u/\alpha_1$	
Costruzioni di muratura confinata con progettazione in capacità	$3{,}0\ \alpha_u/\alpha_1$	
Ponti (§ 7.9.2.1)		
Pile in calcestruzzo armato		
Pile verticali inflesse	$3{,}5\ \lambda$	1,5
Elementi di sostegno inclinati inflessi	$2{,}1\ \lambda$	1,2
Pile in acciaio:		
Pile verticali inflesse	3,5	1,5
Elementi di sostegno inclinati inflessi	2,0	1,2
Pile con controventi concentrici	2,5	1,5
Pile con controventi eccentrici	3,5	-
Spalle		
In genere	1,5	1,5
Se si muovono col terreno	1,0	1,0

Figure 16. The behavior coefficient, according to standard of NTC 2018

The height to length ratio (h/H) of the structure is another parameter that should be considered.
This parameter indicates the effects of the geometric scale of the structure on its seismic response.
The h/H ratio has a direct impact on the distribution of seismic loads and the stability behavior of the structure.
Recommended values according to NTC 2018:

h/H < 1.0 → short and stable buildings

h/H = 1.0 - 2.0 → conventional buildings

h/H > 2.0 → tall structures, sensitive to dynamic effects

Therefore, in this study it can be considered equal to one.

5.3.3. Rigid Diaphragm Analysis

Rigid diaphragms play an important role in the distribution of seismic loads between structural members. In this building, the floor slabs are assumed to act as rigid diaphragms, distributing the forces between the load-bearing elements. In BIM modeling, this effect can be investigated by analyzing the distributed stresses on the slabs.

5.4. Proposed Retrofitting Methods

To reduce the vulnerability of the building, several reinforcement methods have been proposed

- *Adding shear walls*: Increases lateral stiffness and reduces structural displacements.

Shear walls are vertical structural elements that are responsible for resisting lateral forces from earthquakes and wind. These walls are usually made of reinforced concrete and are used in tall buildings to reduce lateral displacements and increase the overall stiffness of the structure.

Advantages:

- Reduce lateral displacement of the building
- Increase structural stiffness and reduce vibrations caused by earthquakes
- Proper distribution of lateral forces to the foundation

Limitations:

- Increases building weight and dead load
- Reduces architectural flexibility due to space occupation
- Requires proper design of connections to beams and columns

- *Using steel braces*: Can play an effective role in controlling horizontal displacements.

Bracing Systems are diagonal steel elements installed in building frames and play an important role in controlling lateral deformation and absorbing earthquake energy. These systems are used in bending frames and steel structures, especially in the retrofitting of old buildings.

Types of Bracing:

Concentric Bracing: Transfers lateral loads directly to the foundation.
Eccentric Bracing: Has a flexible connection that increases the ductility of the structure.

Advantages:

- Reduces lateral displacement of the building
- Improves ductility and increases energy absorption capacity
- Light weight and ease of installation compared to shear walls

Limitations:

- Possibility of reducing architectural space in facades and interior spaces
- Needs to carefully examine connections to prevent buckling of members

- *Reinforcing beam-column connections*: Using FRP or concrete jackets increases the load-bearing capacity.

FRP is a new method for strengthening structural components in which composite fibers (such as carbon, glass, and aramid fibers) are bonded to the surface of concrete or steel to increase compressive, flexural, and shear strength.

Applications of FRP in seismic strengthening:

Flexural strengthening of beams: increases load-bearing capacity and prevents premature failure
Shear strengthening of columns: increases column stiffness and reduces the likelihood of brittle failure
Increases the strength of shear walls: increases shear capacity and prevents cracking.

Advantages:

- Very low weight and no increase in dead load
- Quick installation and possibility of implementation on existing structures
- High resistance to corrosion and environmental conditions

Limitations:

- Sensitivity to high temperatures and fire
- Requires epoxy adhesives and concrete surface preparation
- High cost compared to traditional methods

Depending on the type of this building, it is better to the mixture of all above suggestion among the above methods.

Even without numerical modeling, a qualitative comparison can be made between before and after retrofitting:

Before retrofitting	After retrofitting
Possibility of high displacement of upper stories	Reduction in relative displacement of stories
Increase in earthquake forces in lateral columns	Reduction in critical internal forces
Weakness in beam-column connection	Increase in lateral load-bearing capacity

Figure 17. Comparison of retrofitting and non-retrofitting conditions

Retrofitting Method	Effect on Structural Behavior	Advantages	Disadvantages
Adding a shear wall	Reducing lateral displacement	Increasing stiffness	Increasing the weight of the structure
Use of steel wind brace	Reduces displacement and stresses in the frame	Lightweight, quick installation	Architectural impact
Reinforcement of columns with FRP	Increased strength and ductility	Low-cost method	Fire-sensitive
Increasing beam and column cross-section	Increasing strength and rigidity	Improving structural performance	Need to strengthen foundation
Use of seismic isolators	Reduces earthquake force	Protects the entire structure	High cost

Figure 18. Advantage and disadvantage of retrofitting

Chapter 6

6. Conclusion

This thesis has provided a comprehensive risk assessment for the elementary school in Crodo, focusing on structural stability and potential hazards. The study began with an analysis of various risks that could affect the school, considering both natural and structural factors. This was followed by a detailed structural stability assessment, which examined key influencing parameters and their impact on the safety of the building.

The evaluation of stability control measures and risk mitigation strategies highlighted the importance of proactive interventions to enhance the resilience of the school structure. Various methods were assessed to determine their effectiveness in reducing vulnerabilities, as suggested in the previous chapter. Ensuring that the recommended solutions align with safety regulations and engineering best practices.

A significant contribution of this work is the formulation and application of the assessment model (units), which offers a structured approach to quantifying risk levels and guiding decision-making processes. The results indicate that by implementing targeted mitigation strategies, the overall risk to the school can be significantly reduced.

Despite the research of this study, further research is recommended to refine the assessment model and validate its applicability in different contexts. Additionally, long-term monitoring of structural stability and periodic reassessments will be essential to ensure ongoing safety improvements.
Looking toward the future, advancements in risk assessment methodologies and structural monitoring technologies can further enhance the safety of educational facilities. The integration of real-time data collection, AI-driven predictive models, and automated structural health monitoring systems could provide more accurate and timely risk evaluations. Furthermore, collaboration between engineers, local authorities, and educational institutions will be critical in maintaining and improving school infrastructure resilience.

In conclusion, this thesis underscores the necessity of systematic risk assessment in educational facilities and highlights the role of engineering solutions in safeguarding-built environments. The findings and recommendations presented here provide a foundation for future safety enhancements, ensuring a secure learning environment for students and staff alike. By embracing continuous improvements and technological innovations, we can create a safer and more sustainable built environment for future generations.

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