POLITECNICO DI TORINO

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Master's Degree in Building Engineering

LM-24 Construction Engineering

NUMERICAL ANALYSIS OF SEA CLIFF: THE CASE STUDY OF CERVO (IM)

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Abstract

This study presents a comprehensive numerical analysis of a decaying sea cliff along the SS1 “Aurelia” at Km 634.500 in the Municipality of Cervo (IM), incorporating both back analysis and forecasting carried out the Finite Element Method implemented in the Rocscience RS2. The study area has experienced significant landslide events, notably in November 2023 and March 2024, posing a potential threat to infrastructure and nearby structures. Of particular concern is the "Tana dei Colombi" condominium, situated directly above the cliff, which increased instability risks due to ongoing at the toe of the cliff. A structured approach was adopted, beginning with the collection of site-specific data, particularly the Digital Terrain Model (DTM). The DTM was utilized to extract the section profile of the affected landslide-prone area. This section was then refined and updated in AutoCAD, where multiple layers were defined to ensure accurate representation within the RS2 numerical model. Material properties and geotechnical parameters were obtained through an extensive literature review. The back analysis phase involved replicating a known landslide event from March 2024. The material properties were iteratively adjusted until the failure conditions matched the real event, specifically when the surface reduction factor (SRF) fell below 1 and yield elements concentrated near the detachment zone. In the forecasting phase, the study aimed to predict future cliff instability by simulating progressive retreat of the notch generated by the erosion process. Several incremental erosional stages were modeled to evaluate stability thresholds, identifying potential failure scenarios under continued natural degradation. The results provide critical insights into the failure mechanisms of the coastal cliff.

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1 SLOPE STABILITY

1.1 Introduction

The stability of the rock cliffs has a direct influence on the preservation of natural heritage as well as the safety of people, buildings, and infrastructure, making it a very important concern. One of the most important real-world concerns in geotechnical engineering is slope stability. It refers to the capacity of soil or rock slopes to tolerate gravity and external pressures without sustaining structural damage. The stability of slopes is a fundamental problem in the construction and maintenance of infrastructures such as highways, railways, foundations, and retaining walls, in addition to in natural landscapes where landslides can pose substantial risks.

Slope instability, slope collapse, and landslides are large-scale and complicated concerns that go beyond their prevalence along the shore. Coastal landslides, on the other hand, are common and typically occur close to a cliff. At one extreme, small blocks less than one cubic meter in size detach and fall down an existing cliff face. At the other extreme, the collapse of the whole coastal slope with a cliff at its base can transport several thousand cubic meters of material into the surf zone. Mass movements and landslides play an important role in coastal cliff erosion.

Figure 1.2.1.1 Landslide on cliff facing sea shore (Paul,2011)

Slope stability poses various issues, especially in areas prone to poor environmental conditions and fast development. Natural causes such as heavy rainfall, earthquakes, and slow weathering can speed up slope degradation, making it harder to foresee and minimize possible collapses. The complexities of geological formations in mountain and marine ground hilly, as well as the existence of weak or worn materials, raise the danger of landslides and mass movements. Additionally, climate change has amplified weather extremes, resulting for example in uncertain rainfall patterns that raise groundwater levels and weaken slope strength, or violent sea storms which accelerate the degradation of the rock cliffs aggravating instability.

Safety issues about slope stability are crucial, as failures of slopes can have disastrous repercussions such as infrastructure destruction, human fatalities, and severe economic setbacks. Hazardous slopes near densely inhabited regions or major traffic routes continue to endanger local economy. The unpredictable nature of slope collapses necessitates detailed hazard evaluations, real-time monitoring systems, and the adoption of appropriate mitigation strategies. Balanced infrastructure development with slope safety needs an integrated strategy that includes geotechnical studies, environmental issues, and sustainable engineering approaches.

1.2 Types of Slope Instabilities

Understanding the various forms of slope instability is critical for determining slope stability and adopting appropriate mitigation techniques. Slope instabilities can be classified according to the method of movement, material involved, and failure surface shape. The most prevalent forms of slope failures are:

1) Translational Failure
2) Rotational Failure
3) Toppling Failure
4) Rock fall
5) Flow Failure
6) Lateral Spread

1.2.1 Translational Failure

It takes place along a predefined flat surface with minimal or no ground rotation. Translational slides are primarily controlled by weak surfaces such as joints, bedding planes, or interaction of materials with different shear strength. Translational failures are frequently quick and can affect wide regions, posing considerable threats to infrastructure and safety.

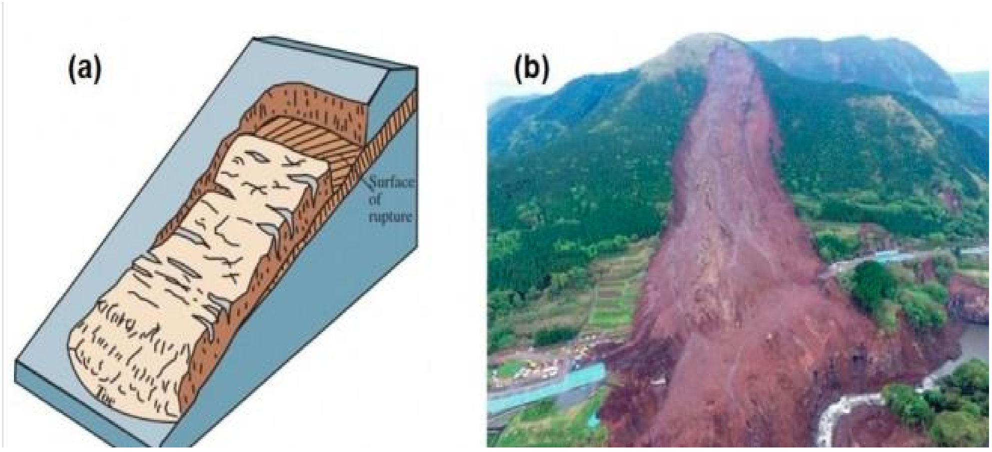


Figure 1.2.1.1 a) Illustration of a translational landslide (USGS, 2004) and b) Co-seismic translational landslide triggered in Japan in 2016 (Highland and Bobrowsky, 2018 by Khang Dang and Kyoji Sassa)

1.2.2 Rotational Failure

Rotational failures are characterized by movement over a curved slip surface and are most common in homogenous, cohesive soils. This sort of failure produces a backward-rotating masses and is commonly found in soft clays and cohesive materials. The movement is frequently connected with ground shear failure, and its three-dimensional geometry is "spoon-shaped". (Refer Figure 1.2.2.1)

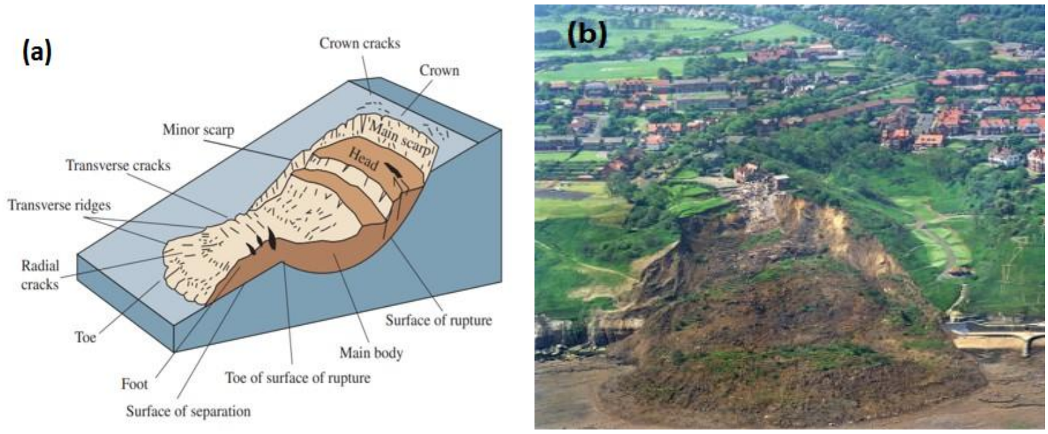


Figure 1.2.2.1 a) Illustration of a rotational landslide (USGS, 2004) and b) The rotational Holbeck Hall landslide landslide, in Scarborough North Yorkshire, England (June 1993)

1.2.3 Toppling Failure

This type of collapse occurs when rock columns rotate forward around a pivot point. It typically occurs on steep, jointed rock slopes with vertical or near-vertical discontinuities. Toppling failures are typical on coastal cliffs caused by undercutting by wave activity.

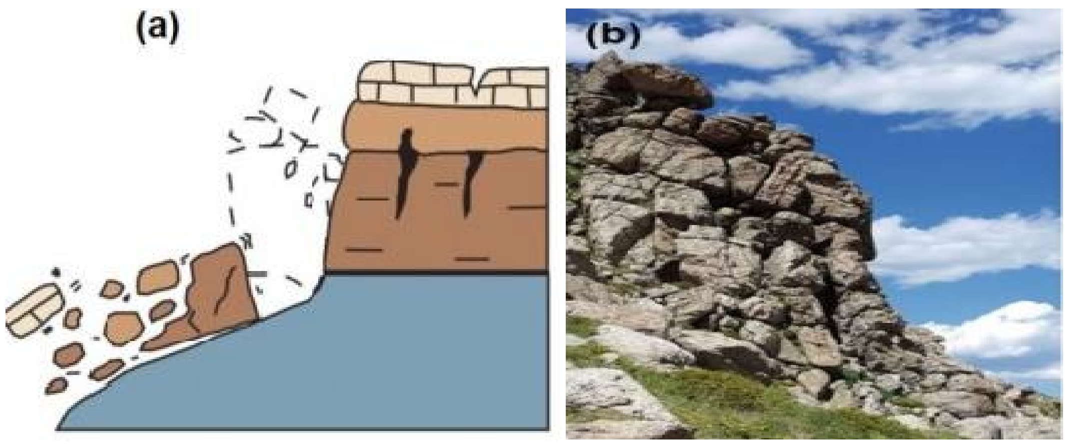


Figure 1.2.3.1 a) Illustration of a topple failure (USGS, 2004), b) Topple failures in granite boulders, Mount Evans, Arapaho National Forest, Colorado, U.S.A. (Highland and Bobrowsky, 2018)

1.2.4 Lateral Spread

Lateral spreads are deformational events generated by liquefaction, which occurs when a saturated soil (often sand) loses strength due to an abrupt shift in its initial stress conditions. As a result, the earth behaves more fluidly than solidly. Such deformations occur on less steep slopes and are typically caused by dynamic stresses such as an earthquake. Lateral spreading is often a progressive phenomenon that happens mostly around shorelines, riverbanks, and ports with loose and wet sandy soils. Infrastructure built on these types of soils is susceptible to substantial harm.

Figure 1.2.4.1 a) An illustration of a translational landslide (USGS, 2004) and b) Lateral spreading example caused by an earthquake in Pakistan

1.2.5 Rockfall

Rock falls happen when individual rock fragments separate from steeps slope faces and fall or bounce downslope. This sort of breakdown is prevalent on coastal cliffs as a result of constant wave erosion and weathering, posing serious risks to those below. Falls are determined by the breaking strength of the discontinuous plane, which decreases with weathering from mechanical propagation and the existence of water. Once dislodged, a rock boulder will follow a certain trajectory determined by its size, shape, and the coverage material onto the slope. The movement type might be free-fall, bouncing, rolling, or a mix of those components.

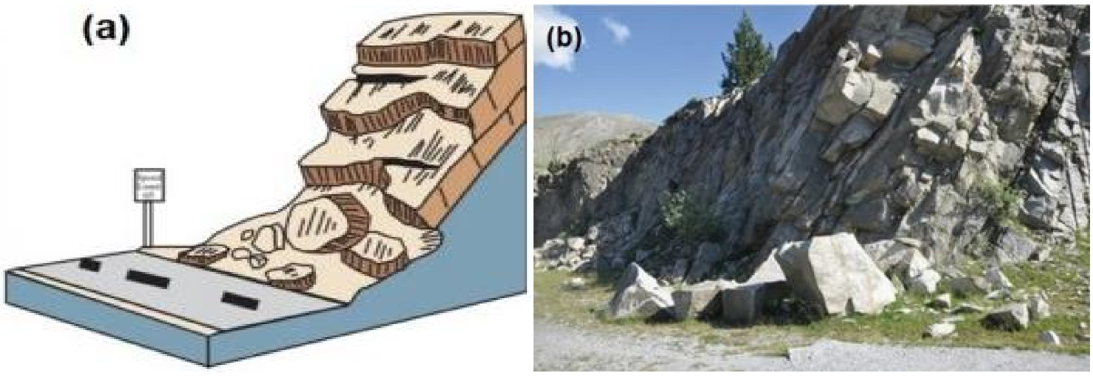
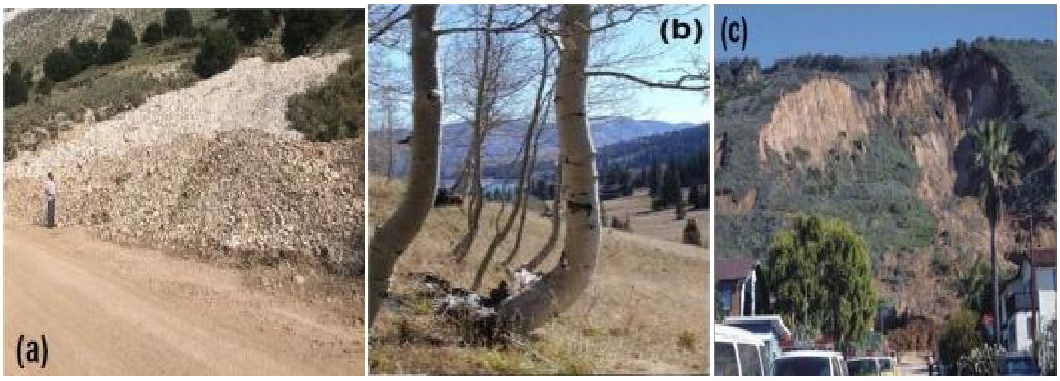


Figure 1.2.5.1 a) Illustration of a rockfall (USGS, 2004), b) Rockfall in Central Pyrenees, Spain (Corominas, 2017)

1.2.6 Flow Failure

This fast, often fatal movement involves wet soil or debris acting like a fluid. For instance, soil creep, debris flows, and earthflows. Flow failures are often caused by heavy rainfall or quick snowmelt, which causes high pressures in the pore water and a decline of shear strength.



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1.3 Factors Affecting Slope Instability

Slope failure happens when gravity and shear loads surpass a material's shear strength. Factors that raise shear stress or reduce shear strength increase the likelihood of failure. High pore pressure, cracking, swelling, clay decomposition, persistent loading (creep), leaching, or the strain softening, weathering, and cyclic loading all lower shear strength. Shear stress can develop as a result of increasing loads placed on the slope, water pressure in fractures, increased soil weight owing to water content, excavation at the gradient's base, and seismic activity. Other influences include rock mass mechanical characteristics, slope geometry, temperature, and erosion. The elements that influence failure of slopes have been explained below:

1.3.1 Rock Mass Discontinuities

Rock slope stability is significantly influenced by structural discontinuities, that are planes or surfaces that indicate chemical or physical modifications in the rock structure. These consist of bedding planes, joints, fractures, fissures, and faults. Discontinuity features like as orientation persistence, roughness, and spacing all influence the kind of slope failure. Repeated or single discontinuities can also cause anisotropy in the rock mass, which influences its stability.1

The alignment of a large geological discontinuity in relation to an engineering component also influences the likelihood of unstable situations. The individual blocks' shapes are determined by the mutual orientation of discontinuities. A discontinuity's orientation is determined by its dip (highest incline to the horizontal) and dip direction (angle of discontinuity face with respect to North). The strike is at right angles to the dip direction, as shown in (Figure 1.3.1.1). Figure 1.3.1.2a Explain the likelihood of planar failure along a rock discontinuity, as the dip angle of discontinuity increases and becomes subparallel to the slope angle, the slope becomes rather stable (figure 1.3.2b). However, increasing the dip angle of the discontinuity makes it more prone to toppling failure. (figure 1.3.1.3c).

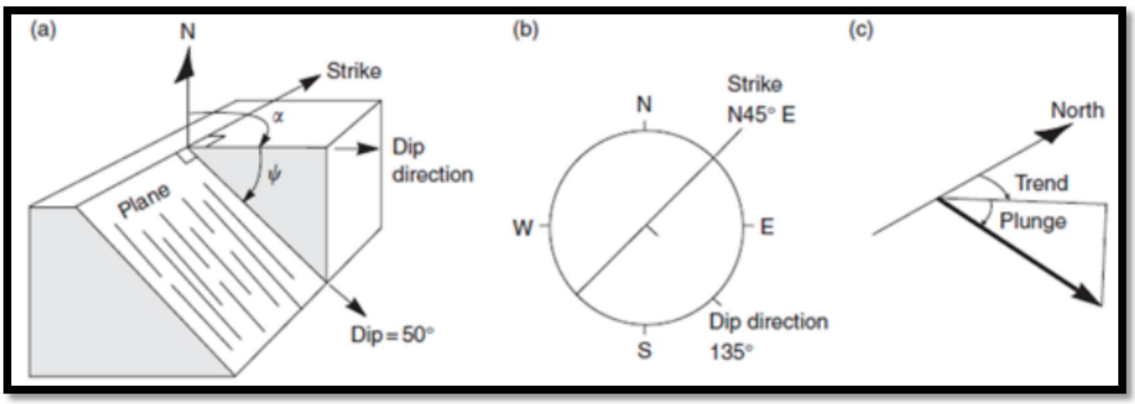

Figure 1.3.1.1 Terminology defining discontinuity orientation (a) isometric view of plane (dip and dip direction, (b) plan view of plane (c) isometric view of line (plunge and trend)
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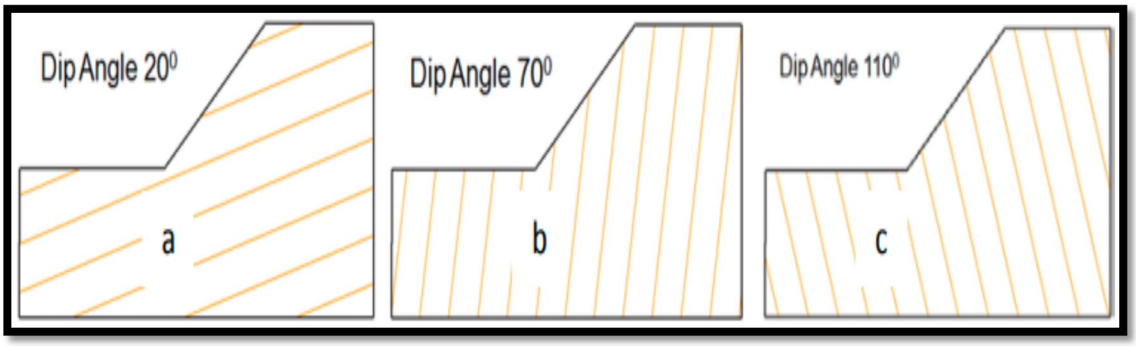

Figure 1.3.1.2 illustrates the effect of discontinuity orientation on the types of slope failure
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The size of blocks able to slide from the face is determined by the persistence of discontinuities as well as the spacing. Furthermore, a tiny region of undamaged rock between low persistence discontinuities can have a favorable impact on stability since the strength of the rock is significantly increased.

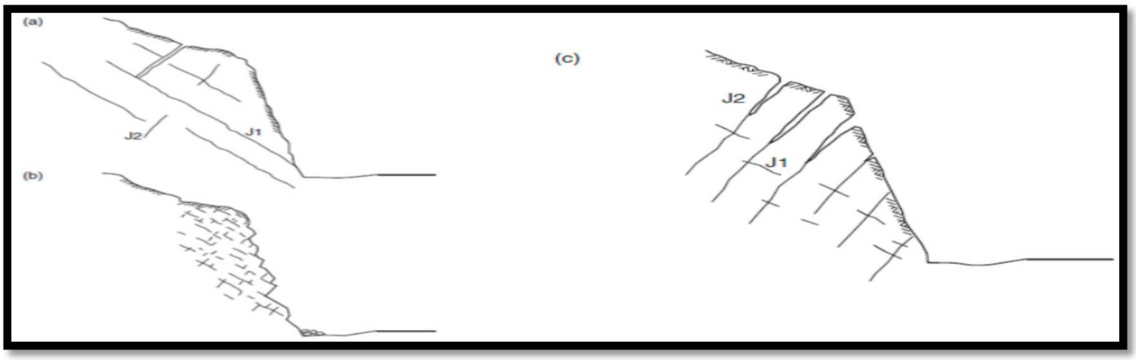

Figure 1.3.1.3 Effects of persistence on slope stability
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1.3.2 Geometry of the Slope

The height and inclination of the slope are important parameters in slope geometry that influence stability. The essential slope height is defined by the material's shear strength, density, and foundation bearing capacity. In general, slope stability decreases as slope height increases because the additional weight raises shear stress near the slope's toe. As the slope angle becomes steeper, tangential stress increases, resulting in stability.

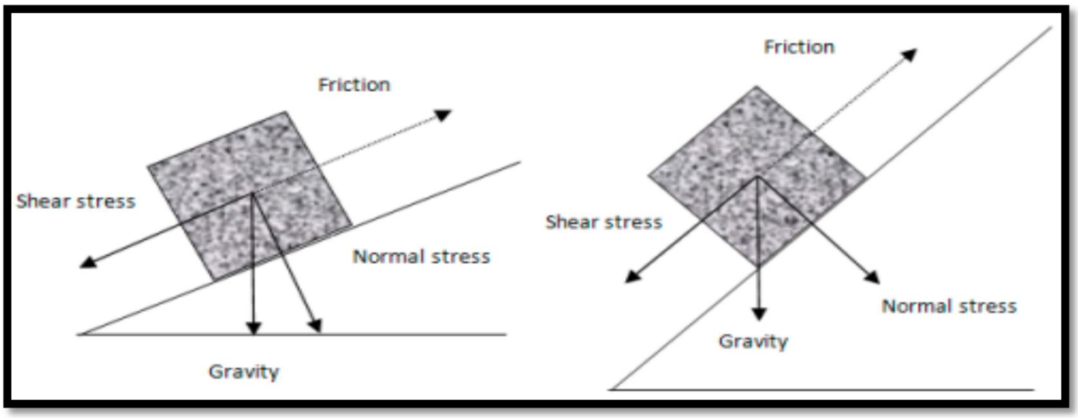

Figure 1.3.2.1 Effect of slope angle on slope stability
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1.3.3 Erosion

Erosion affects slope stability in two ways. Large-scale erosion, such as river erosion at a slope's base, changes the slope geometry and decreases confining stress, raising the danger of failure, whereas localized erosion through groundwater degrades joint fillings and induce weathering, lowering interlock and shear strength. This loss of strength can cause slope failure, and increasing permeability due to erosion might further destabilize the slope.

1.3.4 Vegetation

Plant roots provide a robust network that stabilizes unconsolidated soil, prevents erosion, and removes water, increasing shear strength. Although the weight of vegetation can marginally destabilize slopes with weak roots, vegetation generally improves slope stability. (Coppin and Richards, 1990) Grasses develop rapidly but possess shallow roots; herbs (a leafy green parts of plant) possess deeper roots but are more difficult to maintain; shrubs have deep roots and require little maintenance; and trees have strong roots but grow slowly. The efficiency of vegetation is determined by local circumstances such as slope, hydrology, and type of ground (soil or rock). Removing vegetation can cause higher erosion and slope instability.

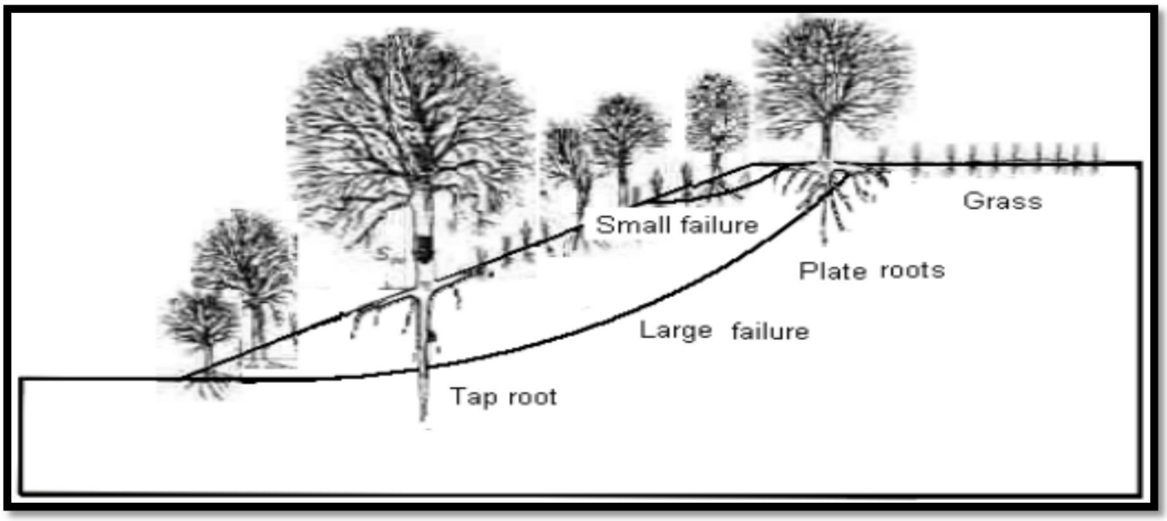

Figure 1.3.4.1 Mechanisms of root reinforcement of grass plants and tree
https://seismicconsolidation.com/wp-content/uploads/2020/03/factors-affecting-slope-failure-1.pdf

1.3.5 Geotechnical Properties of Ground

The ground shear strength, grain/block size distribution, density, permeability, moisture content, plasticity, are all key geotechnical parameters that influence slope stability. The strength of soil or rock has a significant impact on slope stability. It depends on the strain rate, the hydraulic condition, the effective stresses operating on the, the grain stress history, and any variations in water content and density that occur over time. It is made up. Friction is an opposing pull between two surfaces. Cohesion is the effect of particle surfaces adhering together.

The relationship between the peak shear strength **τ** and the normal stress **σ** can be represented by the Mohr-Coulomb equation:

$$\tau = c + \sigma . \tan\phi$$

where **c** is the cohesive strength and ϕ is the angle of friction.

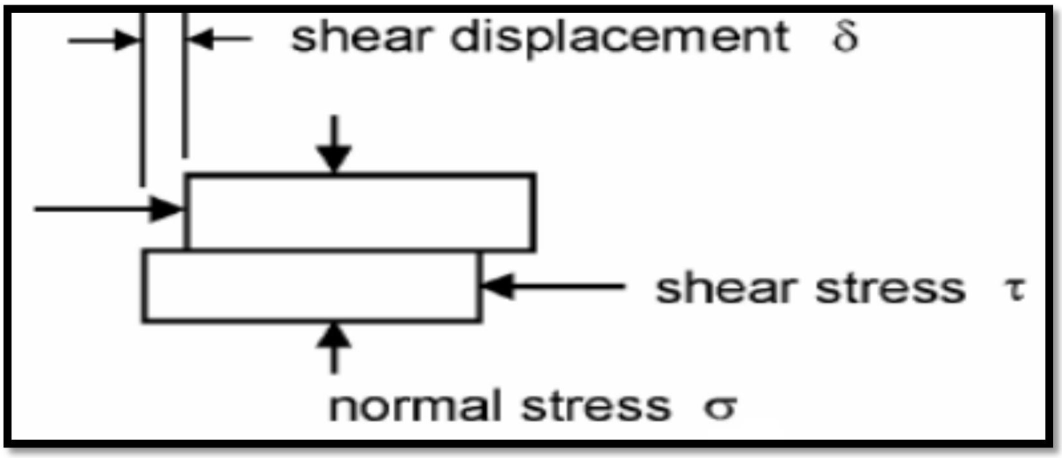

Figure 1.3.5.1 Shear testing of discontinuities or between two plane
https://seismicconsolidation.com/wp-content/uploads/2020/03/factors-affecting-slope-failure-1.pdf

Density is also a key component in slope stability. However, its impact is greater in mining waste dumps, where it is influenced by the mode of deposition, gradation, and loading history. A very minor increase in density can enhance the shear strength of the waste dump, but it also increases the stresses caused by gravity loading.

The permeability of the soil or waste material influences seepage patterns and water levels in the slope. This, in turn, can impact the material's shear resistance depending on the size and morphologies of the particles, degree of compaction, soil gradation, and density. (Campbell, 1975 and Aubeny and Lytton, 2004)

1.3.6 Temperature

Temperature fluctuations also have an influence on the stability of slopes. Large temperature variations can induce rock spalling owing to expansion and contraction. The freezing of water within fissures causes worse damage through weakening the rock bulk, and repetitive freeze-thaw cycles can eventually reduce its strength. Although these impacts are mostly surface-level and normally represent low risk to long-term slopes apart from occasional maintenance, in rare circumstances, surface deterioration may progress into larger-scale slope instability.

1.3.7 Seismic Effect

Seismic waves moving through rock provide extra stress, perhaps resulting in cracks within the rock mass. Earthquake-induced landslides are among the most serious risks associated with seismic activity. Blasting and earthquakes have varied effects on rock slopes throughout time. The first is the rapid co-seismic separation of rock blocks from the sloped face, while the second includes long-term impacts such as crack propagation and rock fracture, which can contribute to subsequent rockfall. The intensity of seismic effects on rock slopes is mostly determined by local rock mass situations, along with the area's geological and topographical factors, which affect the slope's sensitivity to failure. Furthermore, in coarse soil the dynamic actions could induce liquefaction.

1.4 Protection Against Slope Instability

Stabilizing slopes is critical for preventing landslides, weathering, and structural damage. It entails putting in place a variety of measures to keep slopes stable and avoid accidents or damage. Slopes with steeper slopes or erodible soils need extra care and protection. Surface protection, drainage control, slope reinforcement, and rockfall protection systems are the four main categories of protective measures.

1.4.1 Surface Protection

The simplest and cost-effective way for protecting slopes with exposed surfaces is to use plants or mulch. The basic objective of all surface stabilization strategies is to quickly establish a dense plant cover to decrease soil erosion. Native plant types often have cheaper prices and require less maintenance while fitting in with the natural surroundings. Furthermore, several non-native plants have been particularly bred for erosion management and can be useful in this regard.

Brush Layering

Contour brush stacking (Figure:1.4.1.1) is the process of placing live shrub or tree branches in successive horizontal rows along a slope. It can be observed that:

1. Installing branches perpendicular to the slope contour, rather than parallel, improves the resistance to shallow shear failures.
2. Staking is unnecessary.

3. The brush's layers and surfaces can be reinforced using wire mesh or other materials.
4. Brush layers are able to use throughout the fill building process. In this technique, brush layers are deposited, which is followed by a layer of dirt that is distributed and compacted. The cycle is repeated as needed.

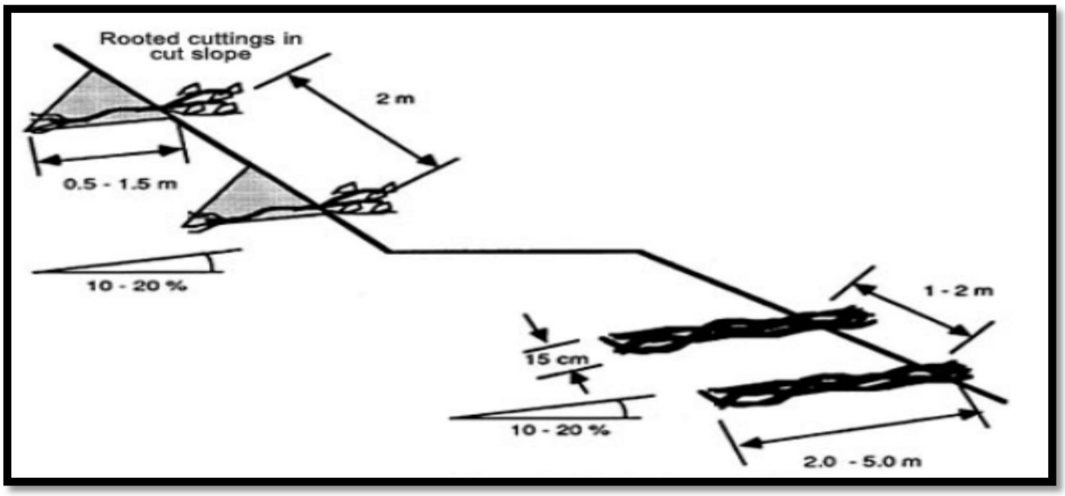

Figure 1.4.1.1 Compacted Bush Layers in Fills
https://www.fao.org/4/t0099e/T0099e05.htm

According to Schiechtl (1978, 1980), there are three primary methods for implementing brush layering:

1. The first option is Roots Plant Brush Layer, which uses brush layers constituted entirely of rooted plants or cuttings. This procedure normally takes between 5 and 20 rooted seedlings per meter. (Refer to Figure 1.4.1.1).

2. The second approach, known as Green Cutting and Branches, uses fresh cuttings or branches from species such as alder, cottonwood, or willow. Cut slopes employ cuttings ranging from 0.5 to 2.0 meters in length, whereas fill slopes use cuttings ranging from 2.0 to 5.0 meters. This approach is very helpful in stabilizing important or sensitive regions.

3. In third strategy, the Combined Method combines the previous two, including rooted seedlings or cuttings with new branches. This combination approach generally requires 1 to 5 rooted cuttings per meter for best stability.

In all three approaches, materials should be positioned with the butt ends slanted downwards into the slope approximately 20%, and the tips extending only a few inches outward. The vertical distance between brush layers can vary from 0.5 to 1.5 meters, based on soil qualities, erosion danger, slope angle, and slope length. A great practice is to reduce vertical width near the base of longer slopes and progressively increase it towards the top.

A variant on the traditional contour brush layering method, which normally aligns brush layers horizontally down the slope, is to place layers at a 10-40% angle. This modification is especially beneficial for moist, deep soils or slopes with numerous little springs because it helps water to drain effectively from the brush layers or berms, reducing stagnation and penetration into the slope.

Installation often begins at the bottom and moves upward. On fill slopes, the method is basic, but the brush layers must be slanted into the slope by a minimum of 20%. Following installation, a fresh dirt layer is applied and compacted. Cut slopes are created by excavating a trench or building a mound. Like fill slopes, work should be done from bottom to top, utilizing material dug from upper berms to fill in and cover lower brush layers.

Site Analysis

To guarantee the effectiveness of any revegetation endeavor, it is vital to establish an overall strategy that takes into account the climate, vegetation, and microsite.

Climatic data should highlight the pattern and level of rainfall. In addition, crucial parameters to assess are average, minimum, and maximum temperatures, the quantity of heating degree days, and the period of frost-free periods.

The vegetation evaluation should look at the adaptation of both native and invasive plant species to the given environment. The emphasis should be on creating a comprehensive inventory of every species of plant present. This study should also document the specific microsites, conditions of soil, and slope orientation in which different species flourish. Important considerations include:

- Which plants may flourish in various environmental conditions?
- Which types of plants are effective at delivering consistent seed yields.
- Which plants root quickly when partially submerged or can recover from roots damaged during construction?
- What species have the most beneficial qualities for mitigating erosion?

Microsite analysis should consider microclimate, slope direction, landform, and composition of the soil. The microclimate is primarily impacted by variations in radiation balance and the environment around it. Variations in radiation exposure have a direct influence on microclimatic conditions and temperatures at the surface, which are both critical for plant viability. For example, changing the surface color or adding a vapor barrier can have a major impact on these circumstances. Installing a vapor barrier to reduce moisture loss might cause higher surface temperatures. In contrast, employing lighter-colored surfaces can reduce the quantity of absorbed radiation, so assisting in balancing the temperature increase. To get an improved knowledge of how microclimate and vegetation interact. Geiger (1961, 1966)

Perspective and topography can help determine whether specialist treatments are required for plant development or site stability. Proper slope preparation may be required to ensure good vegetation establishment. Mapping wet and dry zones aids in identifying locations that may require specialized drainage solutions or seed combinations. Similarly, slopes steeper than 40 degrees are usually difficult to vegetate unless they are made of worn bedrock or constant rocky subsoil. Evaluating the level of surface erosion will assist establish if the region requires plants with shallow root systems or species with deeper, stronger roots for better stability.

1.4.2 Measures Against Landslide

Several measures can be taken for preventing, controlling, or mitigating the effects of large-scale downward displacement of soil, rock, and debris. They encompass engineering actions or non-engineering action (management measures).

Engineering and structural methods for slope stabilization include the design and execution of mechanical and structural solutions. These strategies try to avoid or reduce landslides, soil erosion, and slope collapse by either decreasing the driving forces that cause instability or increasing the resisting forces that maintain slope integrity.

- Excavation and Fill Methods for stabilizing slopes include cutting and refilling. This may include discovering the base (toe) of an earth flow until repeated minor collapses result in a naturally stable slope, removing and replacing failed material with less heavy, more durable substances, cutting into the higher portions of a mass failure to reduce weight, and adding fill to reinforce the slope's lower sections. These approaches are frequently combined with additional load-bearing or supporting structures to improve overall slope stability.

- Drainage methods aim to eliminate or channel surface water to increase slope stability. Draining tension cracks, using rock fill placed over filter cloth to prevent water from rising into the road foundation, establishing trench drains, perforated horizontal drains, or drainage tunnels, and erecting vertical drains or wells that release water by siphons or pumps are some of the techniques. Furthermore, electro-osmosis, which uses direct electrical current between well sites and steel rods positioned in between, can be utilized to expedite drainage in low-permeability soils.

- Support structures include retaining walls, piles, buttresses, counterweight fills, crib walls, bin barriers, reinforced soil, and soil or rock anchors that are pre-stressed or post-tensioned (Figure 1.4.2.1).

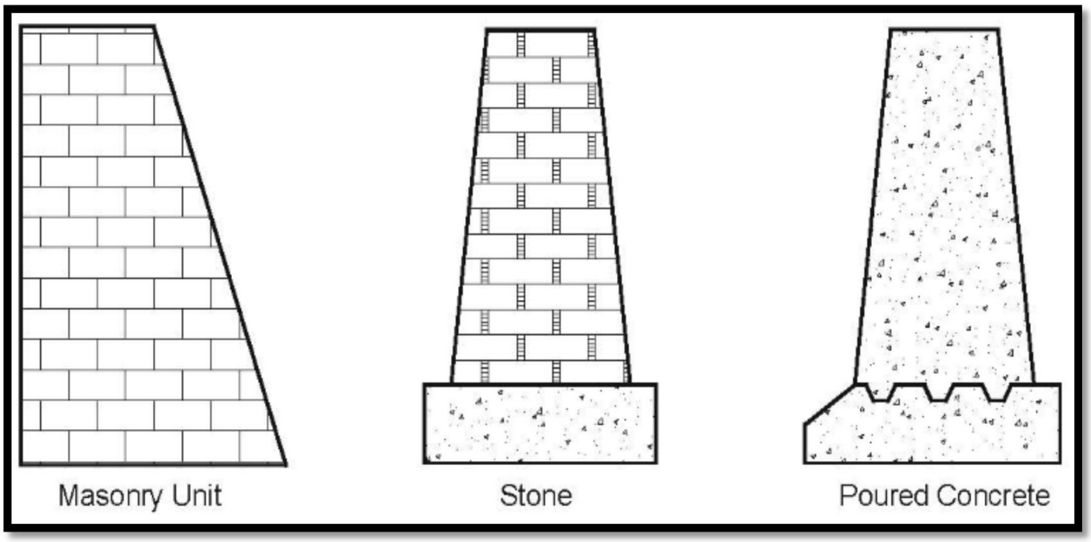

Figure 1.4.2.1 Types of retaining walls
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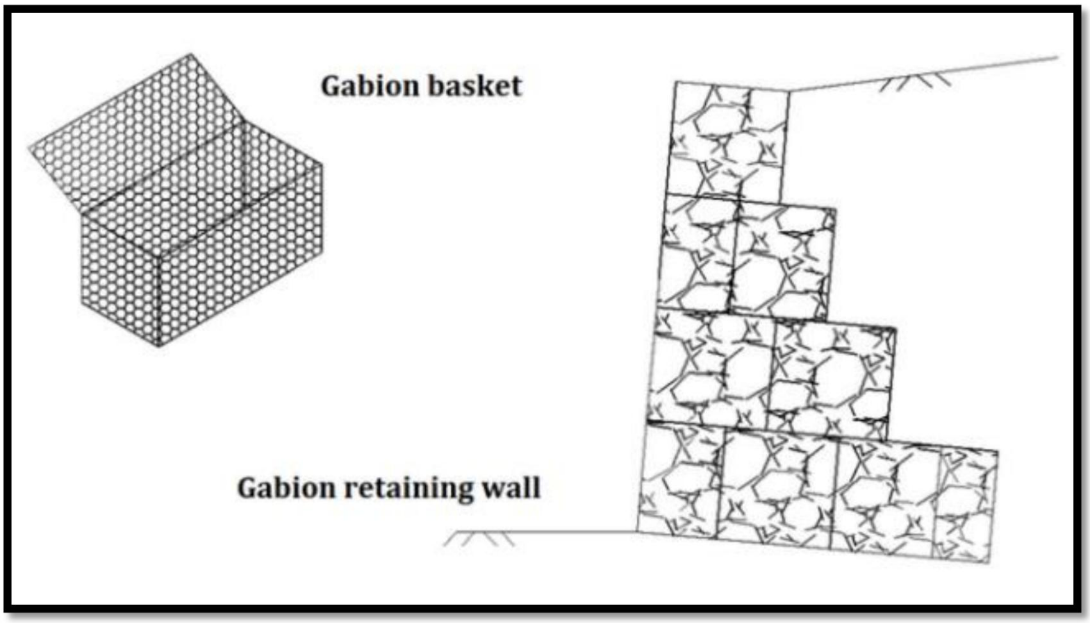

Figure 1.4.2.2 Gabion wall
https://www.fao.org/4/t0099e/T0099e05.htm

- A retaining structure's aim is to offer stability against sliding or failure, as well as protection against scour and erosion on a slope, toe, or cut face. The standard retaining construction on forest roads is a gravity retaining wall, which resists earth pressure using the force of its own weight. Excavation and/or fill volume can be greatly decreased, especially on steep side slopes. The size of cribs or retaining walls ought to be between 1/6 and 1/10 of the total moving mass to be preserved. To be functional, the foundation or base should generally extend at least 1.2 to 2.0 meters below the slip plane. The pressures operating on a retaining wall are comparable to those occurring on a natural slope. As shown in Figure 1.4.2.3, resistive forces comprise water pressure (Pw), passive soil pressures (Pp), sliding friction (F), foundation pressure (Pf), and driving forces water pressure (Pw), active soil pressure (Pa), weight (W), and surcharge load (L).

- Additional Methods: specialized approaches can improve slope stability. Grouting is used to reduce soil permeability, which keeps groundwater from entering failure zones. Chemical stabilization, which is commonly achieved through ion exchange techniques, entails injecting high-pressure targeted solutions into unstable areas or tightly spaced pre-drilled holes inside movement zones. Clay soils can be strengthened in some situations by heating or baking them, while soil freezing can give temporary stability. Localized electro-osmosis can form in-situ anchors or tie-backs, while reducing natural electro-osmotic activity can aid to reduce excess groundwater pressure. Additionally, controlled blasting can be utilized to break up failure surfaces and improve drainage.

Implementing any of these stabilizing approaches needs thorough, site-specific studies of the soil mechanics, groundwater conditions, and bedrock properties at the site. approaches may be rather costly; furthermore, the long-term efficiency of these systems is greatly dependent on the design engineer's skill and the amount of maintenance undertaken following construction. As a result, avoiding places that require structural stabilization will lead to considerable cost savings both in the short and long term, and the most important chance to decrease landslide hazards comes in the route design phase.

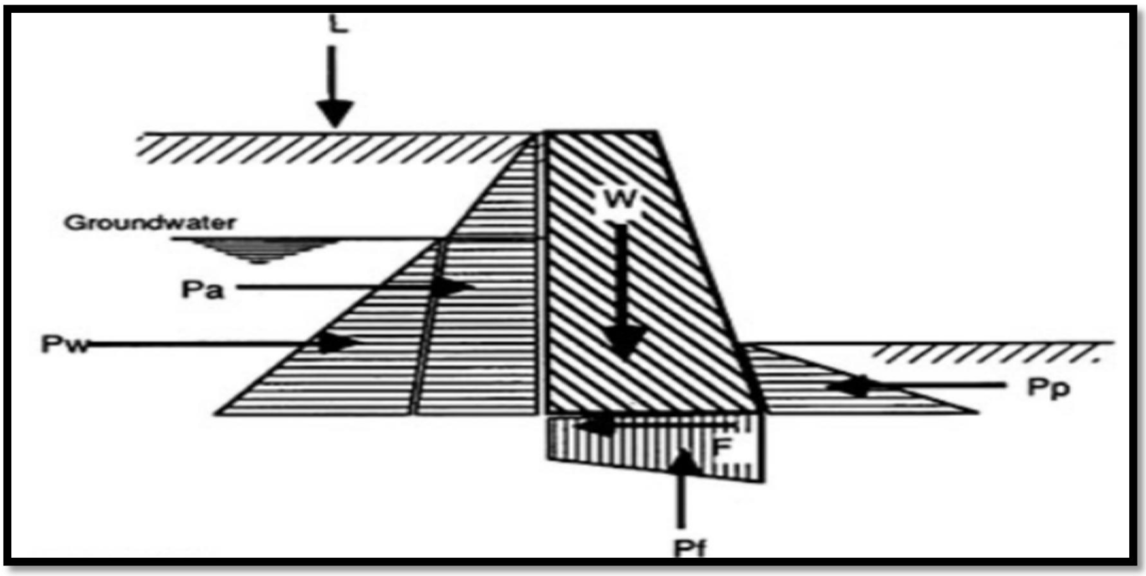

Figure 1.4.2.3 Forces on retain wall structures, https://www.fao.org/4/t0099e/T0099e05.htm

2 COSTAL CLIFFS

The word "coastal cliff" refers to a highly sloped landform where higher terrain meets the shoreline. These cliffs are significant geomorphological formations that occur along nearly 80% of the Earth's coasts. Coastal cliffs are steep, rocky formations that rise abruptly from the beach, generated by the continual action of marine and atmospheric factors. These landforms are notable because they represent dynamic interfaces between terrestrial and marine habitats, frequently displaying distinctive geological formations and ecosystems. Coastal cliffs may be found all throughout the world's coasts, with prominent examples include the White Cliffs of Dover (UK), the Algarve Cliffs (Portugal), and the Amalfi Coast. They have an important function in coastal morphology, sediment supply, and biodiversity.

Having 60% of the world's population residing in coastal areas, erosion of the coastline is seen as a worldwide issue. In fact, roughly 70% of all sandy shores about the globe are recessional (Bird, 1985). Around 85 percent of the United States east coast border beaches (excluding developing spit regions) have undergone erosion during the last century (Douglas & alii, 2004). Massive erosion is also extensively reported in California and the eastern part of Mexico (Douglas & alii, 2004). Europe also suffers various negative repercussions owing to coastal destruction, particularly the realization that an area of roughly 15 square kilometers per year is predicted to be wasted or badly affected by erosion (Doody & alii, 2004; Farrugia, 2006). Furthermore, between 1999 and 2000, a total of 275 dwellings had to be evacuated due to coastal erosion, while another 3000 houses had their value on the market decline by 10%. In addition, in 2004, around twenty thousand kilometers of shoreline faced significant retreat rates (Doody & alii, 2004; Farrugia, 2006)

Coastal erosion causes the formation of cliffs. Weathering degrades the rock, erosion undercuts the foundation of the cliff, and mass movement transports debris down to the shore. (Refer Figure 2.1)

Geology influences the pace at which cliffs recede. Hard-resistant rocks will retreat slowly; for example, the granite cliffs at Lands' End in Cornwall erode by just about 9 cm per year. Whereas the soft boulder clay cliffs in the village of Happisburgh on the North Norfolk coast (Norwich) are eroding at 3 meters per year, and the Holderness Coast in Yorkshire is eroding at roughly 2 meters per year, making it one of the fastest eroding coastlines in Europe.

Figure 2.1 Erosion undercuts the foundation of the cliff(Alan,2016)

2.1 Formation and Evolution of Coastal Cliffs

Most of the cliffs found along modern coastlines are relatively recent geological formations, having developed after the last ice age—the Wisconsinan stage of the Pleistocene epoch or during earlier Pleistocene sea-level rises (refer to Minard, 1971). Approximately 21,000 years ago, the Earth's climate was significantly colder, marking the final phase of a major glacial period (Peltier, 1999). During this time, nearly 44 million km³ of seawater was stored on land in the form of massive ice sheets and glaciers that blanketed vast regions of the planet. This large-scale removal of water from the oceans led to a global sea-level decline of around 120 meters.

As the climate warmed following the Wisconsinan stage, the vast ice sheets and glaciers began to melt, releasing meltwater that flowed back into the oceans, causing a global rise in sea level. This worldwide phenomenon, linked to the total volume of water in the oceans, is known as eustatic sea-level change. Between 21,000 and approximately 5,000 years ago, the sea level increased at an average rate of nearly 1 cm per year (Fairbanks, 1989). Since then, the rise has decelerated but has persisted at a rate of about 2 mm per year over the past century (Cabanes et al., 2001). As the shoreline advanced inland, wave action relentlessly eroded the elevated terrain, creating a gently sloping wave-cut platform just below sea level, capped by a sharp drop forming a sea cliff at its front. A comparable process unfolded in the Great Lakes basins as they filled with water during the melting of glacial ice.

While it may be appealing to attribute the formation of coastal cliffs solely to marine or lacustrine erosion, subaerial processes can be just as influential—if not more so (refer to Nott, 1990). The morphology of a coastal cliff, particularly its gradient, results from the interaction between oceanic and terrestrial forces. Emery and Kuhn (1982) suggested that the predominant agent of coastal cliff erosion (whether marine/lacustrine or subaerial) and the level of its activity (active or inactive) can be identified through the cliff profile. A steep, sharply crested, bare cliff face with minimal debris at its base suggests an actively eroding coastal cliff primarily shaped by marine action (such as wave undercutting). In contrast, a convex or sigmoidal profile with a rounded crest and accumulated talus at the base points to an inactive or abandoned coastal cliff where subaerial forces (like surface runoff, erosion, and landslides) dominate.

Fluctuating dominance between marine and terrestrial processes throughout glacial-interglacial cycles leads to composite cliff profiles, combining steep, wave-eroded segments with convex, sub aerially eroded sections at varying elevations (Trenhaile, 1987, pp. 178-187; Griggs and Trenhaile, 1994). The unique characteristics of coastal cliffs and bluffs emerge from this interplay between subaerial and marine dynamics, alongside the composition of the cliff materials. Whether a cliff develops a vertical free face depends on the relative influence of these two distinct processes (Pethick, 1984).

2.2 Processes

Rising sea levels and wave activity are critical variables driving the evolution of coastal cliffs from their early creation to their fully mature phases. Without the effect of these marine or lacustrine processes, a coastal cliff is considered inactive and deteriorates gradually. During active erosion, various additional contributing elements, mostly of terrestrial origin, might influence the evolution of cliff building. These mechanisms are frequently complex and can cause a variety of outcomes depending on the environment..

Their importance is heavily impacted by the rock type and structural composition of the cliff, and they may only exist under particular circumstances or in certain regions. As a result, coastal cliffs have a wide variety of morphologies and levels of stability. To effectively interpret and forecast the behavior of a specific coastal cliff, it is often important to perform rigorous study and get a full grasp of the geological mechanisms at action..

The process begins with a section of land sloping down to the sea; weathering processes like freeze-thaw degrade the rock. Erosion will occur at the cliff base between the high and low watermarks. The erosional processes here include hydraulic action, in which the sheer power of the water penetrates rocks and weakens them from within, and abrasion, in which the sea hurls shingle against the cliff, scratching and scraping away bits of rock. This erosion continues, and rock will ultimately break away from the cliff foundation and pile on the beach, before being removed by damaging waves, creating a wave-cut notch. This wave-cut notch will expand, left the cliff above it unattended. The wave-cut notch eventually becomes so wide that gravity causes the overhanging rock to fall; the cliff above has already been undermined by weathering processes.

Hydraulic action, abrasion, and weathering caused by freeze-thaw cycles will repeat the wave-cut notch development and cliff collapse processes, forcing the cliff to recede. At cliff retreats, the height normally increases since the area below to the sea is dipping, and the land below has already been abandoned.

As the cliff recede, it creates a wave-cut platform that is frequently submerged at high tide. This is the cliff's old base. Areas of the wave-cut platform will be relatively smooth owing to abrasion from the waves that enter, while other areas will be considerably more rough and maybe coated in algae with barnacles.

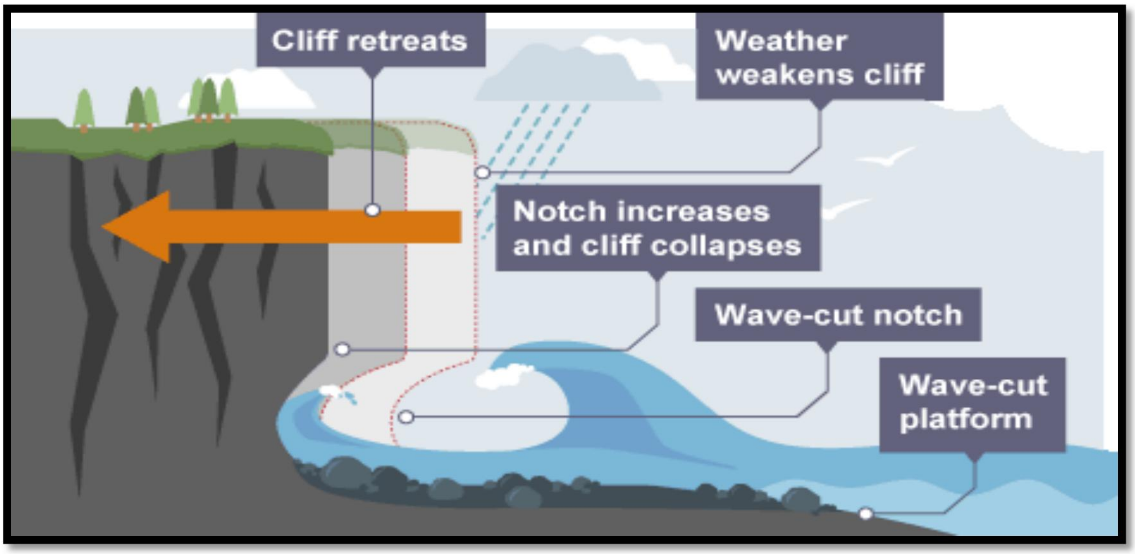

Figure 2.1 Degradation of Coastal Cliff
https://quizlet.com/gb/219421903/formation-of-wave-cut-platforms-diagram/

2.3 Factor Affecting Coastal Erosion

Following are the three main factors which effect the coastal erosion.

2.3.1 Water Level Change:

Sea level change is a dynamic process driven by various factors, both natural and anthropogenic. It refers to the rise or fall of the Earth's oceans in response to climatic, geological, and environmental shifts. Over geological time scales, sea level has fluctuated significantly due to changes in the volume of water in the oceans and alterations in the volume and shape of the ocean basins. These fluctuations have played a major role in shaping coastal landforms, including cliffs, shorelines, and sedimentary features.

Sea-level variation is critical to the evolution of current sea cliffs, and it may become even more essential in the future if gloomy global warming forecasts are realized.

Historical data suggest a ecstatic sea-level rise of 1 to 2 millimeters each year during the past century. (Emery and Aubrey, 1991), whereas more recent satellite measurements demonstrate a higher rate of 3.2 mm/yr (Cabanes and others, 2001). Despite these magnitudes may not appear to be very big, they can result in numbers of horizontal shoreline transgressions that are several times greater, particularly over gently sloped coastal plains, thus the increase plays a key role in the future destruction and flooding of many coasts. For instance, over the last 8,000 years or so in the low-relief areas of the east coast of the United States, although sea levels increased by around 130 meters, the shoreline receded by 130 kilometers in certain places. As a result, the average ratio of coastal retreat to sea-level increase for this time period was 1000:1, indicating that 1 m of retreat occurred for every 1 mm of sea-level rise. Furthermore, many experts predict that global warming will hasten the increase of eustatic sea levels. (Houghton and others, 2001).

The main types of sea level changes are reported below:

- **Eustatic Sea Level Change**

Global sea level changes are transforming sea level that occur uniformly across the planet and are mostly caused by changes in ocean water quantity. This change may occur owing to:

- Thermal expansion: As the climate heats, water expands because of the temperature increase, resulting in a higher sea level.
- Melting glaciers and ice sheets: When temperatures rise, glaciers and polar ice caps melt, adding water to the oceans and raising sea levels.
- Changes in ocean volume: Processes such as ocean basin expansion or variations in tectonic activity can modify the ocean's capacity, causing sea levels to increase or fall.

- **Isostatic Sea Level Change**

Regional or local sea level rise occurs as a result of mass redistribution on Earth, which is frequently caused by the melting or expansion of ice sheets. When enormous ice masses, such as those seen during glacial periods, melt, the Earth's crust, which has been compacted by the weight of the ice, begins to rebound or "rise" in reaction. This process can result in local sea-level rise near locations where ice formerly existed, as well as widespread sinking in areas where the crust is under less pressure.

- **Tectonic Sea Level Change**

Tectonic factors, such as earthquakes, volcanic activity, or movements in the Earth's crust, can also cause sea level variations. Tectonic movements may cause coastal regions to sink or rise. For example, the sinking of a coastal area due to an earthquake may result in relative sea level increase in that location. Conversely, coastal uplift can cause relative sea level to decline.

- **Historical Sea Level Changes**

Historical sea level variations are long-term variations in global or regional sea level over geologic and historical time scales. Natural factors such as glacial and interglacial cycles, geological activity, and ocean temperature variations all contribute to these shifts. Historical sea level variations have profoundly affected the Earth's coasts, driven by phenomena such as ice sheet expansion and melting, saltwater thermal expansion, and crustal movements.

- **Post-Ice Age Sea Level Rise**

Following the previous Ice Age, sea levels increased drastically as glaciers melted, releasing massive volumes of water into the oceans. During the Holocene Epoch (the last 10,000 years), sea levels progressively risen by around 120 meters (394 feet) to their current level.

- **Glacial and Interglacial Cycles**

During glacial, sea levels were much lower because much of the Earth's water was trapped as ice. During interglacial eras, however, sea levels rose as ice sheets melted. During glacial-interglacial cycles, eustatic sea levels fluctuated significantly, reaching up to 130 meters in certain occasions. These changes have had a profound impact on the creation of coastal cliffs and coastal erosion.

In recent history, notably since the Industrial Revolution, human actions such as the usage of fossil fuels have resulted in higher concentrations of greenhouse gases, leading to global warming. This warming has increased two major processes:

- Thermal Expansion: Rising sea levels are caused by the expansion of heated saltwater.
- Glacier and Ice Sheet Melting: The increased melting of polar ice sheets, notably in Greenland and Antarctica, has released massive volumes of freshwater into the oceans, driving sea levels even higher.

Satellite observations show that the worldwide average sea level has been increasing at a pace of around 3.3 millimeters per year since the early 1990s. This rate is likely to increase in the future decades.

The main effects of the sea level change are:

- **Coastal Erosion**

Higher sea levels can cause more extreme coastal erosion because waves can go farther inland, undermining cliffs and shorelines. This process can cause coastal cliffs to recede, leaving the area vulnerable to more wave action and erosion.

- **Flooding of Low-Lying Areas**

Coastal people and ecosystems in low-lying areas are especially vulnerable to increasing sea levels. Coastal plains, deltas, and islands may be inundated, resulting in human relocation and wildlife habitat loss.

- **Changes in Coastal Landforms**

As sea levels rise, the morphology of coasts changes. Wave-cut platforms can be inundated, and sea cliffs can retreat. Coastal cliffs may disintegrate more quickly in some regions as sea levels rise, increasing the frequency and intensity of wave impact.

Sea level rise is predicted to continue throughout the twenty-first century, with estimates ranging from 0.3 to 1 meter by 2100, depending on future greenhouse gas emissions. Coastal communities, notably those in developing nations, face the possibility of major relocation and infrastructural destruction.

Rising or falling sea levels, whether caused by eustatic or tectonic shifts, have a significant influence on the stability and development of coastal communities. Understanding these processes, as well as their historical and projected patterns, is critical for successful coastal management and mitigation efforts against the negative consequences of sea level rise.

2.3.2 Weathering

Coastal cliffs are subjected to a harsh weathering environment if they are repeatedly wet by saltwater spray or runoff from the surface, followed by periods of drying and warmth. The process of weathering is accelerated when the surface materials is fragmented. In addition, cliff-forming material may have weathered under the original ground surface prior to its creation. Weathering often weakens cliffs and makes them more prone to erosion. Weathering effects are often eclipsed by erosion from waves or slope collapse, although they might become dominant under some situations.

If natural surface water is the primary weathering agent, continually wetting-drying cycles may weaken the last few centimeters of the cliff face, especially in the presence of expandable clay minerals that cause surface fissuring, leading to more infiltration, as well as slaking and the formation of prismatic blocks. (Quigley and others, 1977; Hampton and Dingler, 1998). Infiltration can soften the sediment and induce thin slides or flows, whereas intact blocks fall in response to the pull of gravity. Hutchinson (1973) stated that it is impossible to regulate weathering directly, thus reinforcement of worn cliffs should be tackled through other ways, like toe stabilization.

As salt spray repeatedly wets a cliff, the stresses created within voids as salt crystallizes or is heated are more critical than the chemically corrosive effects of salt.

(Bryan and Stephens, 1993; Johannssen and others, 1982; Wellman and Wilson, 1965). These stresses can mechanically dissolve the cliff face, resulting in a weak, crumbling layer.

Johannssen and others (1982) In their research of coastal cliffs on Oregon's temperate coast, they referred to the crystallization process as "salt-crystallization weathering" and the heating effect as "salt-expansion weathering." It is important to note that drying is more important than simply being exposed to salt water. Johannssen and others (1982), this position is supported by a situation in which an uncovered sandstone bedding plane eroded to a rough surface inside the spray zone, although it was smoother below in the intertidal zone (insufficient drying) and above (insufficient wetting). They also found higher retreat rates along south-facing coastal cliffs exposed to the sun, even when sheltered by waves, than along north-facing, sun-shielded cliffs. Where the salt on the cliff was washed away by fresh-water drainage, retreat was gradual.

Bryan and Stephens (1993) observed that the beach platform seaward of the coastal cliff at Hanauma Bay, Hawaii, is broadest where the cliff gets the most severe daily warming and, as a result, endures the most severe salt weathering.

Figure 2.3.2.1 Ground-water discharge at the base of a coastal cliff that is underlain by impermeable rock has eroded a low notch, which undercuts and potentially destabilizes the cliff. Cliff is about 3 m high. https://pubs.usgs.gov/pp/pp1693/pp1693.pdf

2.3.3 Waves

Waves are energy-driven movements of water generated primarily by wind blowing across the surface of the sea. They play a crucial role in shaping coastlines through erosion, transportation, and deposition of sediments.

From a procedural standpoint, wave activity sets coastal cliffs apart from inland cliffs, whose formations are shaped solely by terrestrial processes such as surface runoff, groundwater seepage, and slope instability. When waves strike the base of a cliff, they can either directly erode the cliff material or remove loose debris that has accumulated at its base. Both scenarios contribute to destabilizing the cliff, eventually triggering the collapse of the overlying layers. Understanding the influence of waves on coastal cliff erosion necessitates an analysis of the offshore wave dynamics, and then how these wave patterns adapt to variations in storm intensity and shifts in global climatic conditions.

Due to explicit nature of wave, divided into 5 types.

- **Constructive Wave**

Constructive waves are distinguished by their low-level energy, lengthy wavelengths, and shallow wave height. They often develop in calm weather conditions and become more common throughout the summer. These waves crash softly on the shore, with a strong swash (water moving up the beach) and a weaker backwash (water moving back into the sea). Constructive waves deposit silt and build up beaches, forming a barrier against erosion. Although these waves have minimal direct influence on cliff erosion, they do serve to buffer its consequences by constructing natural barriers that decrease the effect of destructive forces on coastal cliffs.

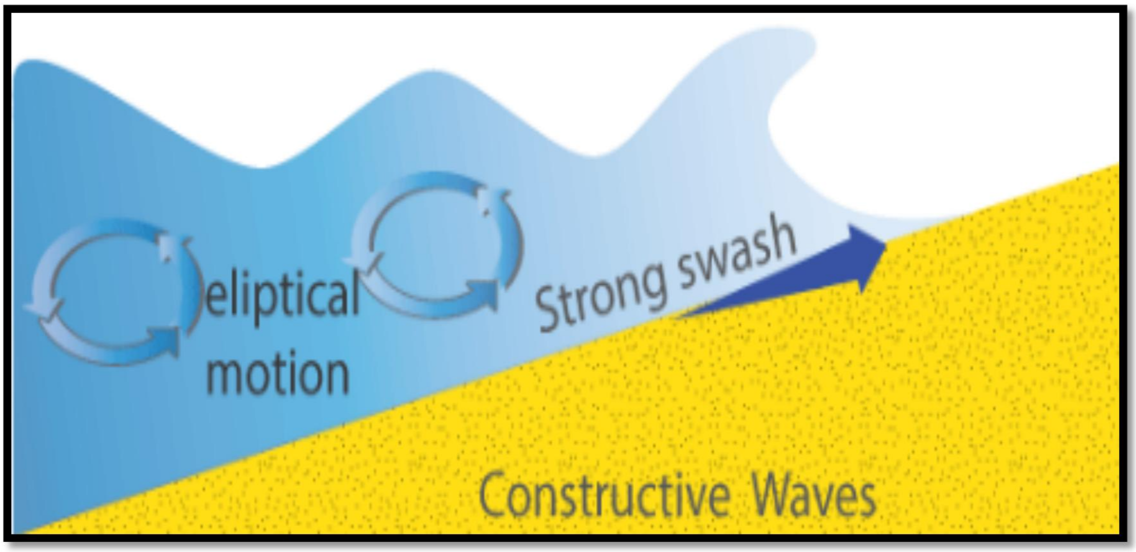

Figure 2.3.3.1 Constructive Wave
https://i-study.co.uk/igcsegeography/coasts.html

- **Destructive Wave**

In contrast, destructive waves are highly energetic waves with shorter wavelengths and towering, steep profiles. They are often produced high-energy weather events and are more abundant in the winter. Destructive waves feature a weak swash and a strong backwash, which remove material off the beach and the base of coastal cliffs. Repeated pounding from damaging waves destabilizes cliffs, resulting in undercut at the base and eventually the collapse of the overlaying material. These waves are the principal agent of cliff erosion, creating the shape of coastal landscapes throughout time.

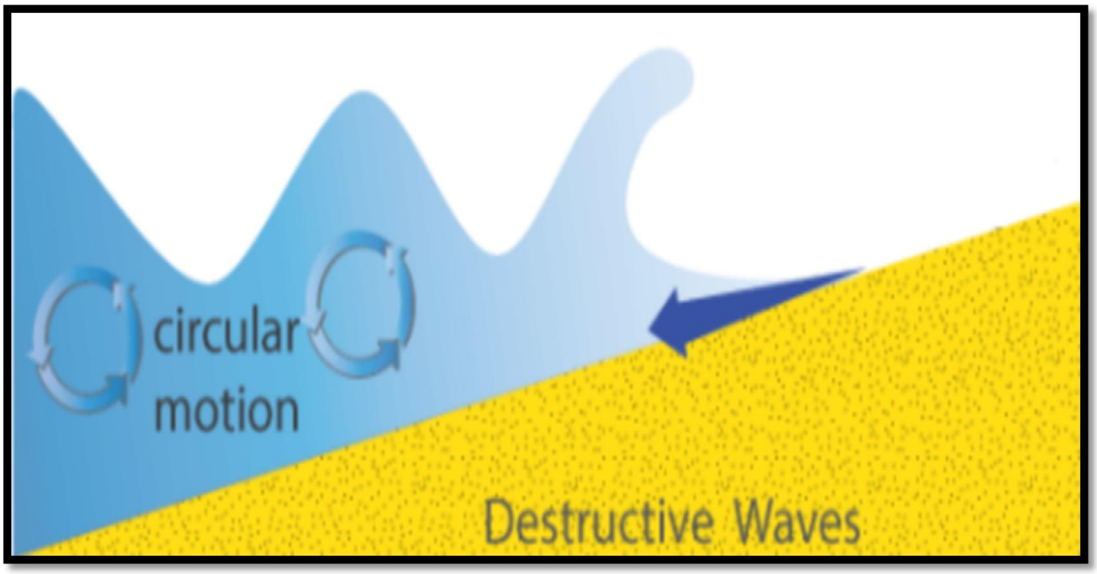

Figure 2.3.3.2 Destructive Wave
https://i-study.co.uk/igcsegeography/coasts.html

- **Wind Generated Wave**

These are the most prevalent sort of waves, caused by the exchange of energy between the wind and the surface of the water. Wind-generated waves' size and power are controlled by a number of parameters, including the speed of the wind, duration, and distance. Wind-generated waves can also be classified into two types: sea waves, which develop in open water and tend to be erratic, and swell waves, which travel great distances and are more consistent in shape. These waves consistently contact with coastal cliffs, imposing pressure and eventually eroding material at the base, resulting in cliff instability and retreat.

- **Tidal Wave**

Tidal waves are created by the moon and sun's gravitational pull, resulting in periodic increases and dips in water levels. Although tides are essentially vertical motions, their interaction with coastal landforms can result in powerful tidal currents that intensify wave activity. These waves can promote erosion by increasing wave energy near cliffs during high tides or storm surges. Cliffs with large tidal ranges may face greater severity and frequency of erosion owing to extended wave exposure.

- **Tsunamis**

Tsunamis are long-wavelength, high-energies waves produced by seismic events such as undersea earthquakes, volcanic eruptions, and submarine landslides. Tsunamis, unlike wind-generated waves, contain huge quantities of energy because of their long wavelengths and may move over whole ocean basins at fast speeds. When tsunamis reach the coast, their energy concentrates, generating a rapid increase in wave height and deadly coastal damage. They may erode cliff bottoms quickly, removing protecting materials and causing large-scale slope collapses.

3 Case Study of Cervo (IM)

3.1 Introduction

Cervo is a beautiful coastal village located in the Liguria region of northern Italy, situated along the Italian Riviera. Known for its stunning sea views, historic architecture, and cultural heritage, Cervo offers a delightful destination for tourists seeking a mix of beach relaxation and cultural exploration.

The hillside village of Cervo is situated within the Province of Imperia and has a population of around 1,100 residents. It stands at an elevation of 67 meters above sea level and is included in the list of Borghi Più Belli d'Italia, which is considered as most beautiful villages in Italy. Places of interest nearby include the towns of San Bartolomeo al Mare, Cervo, Diano Castello and Andora.

The SS1 "Aurelia" is a significant state highway in Italy, stretching approximately 697 kilometers and connecting Rome to the French border, following the coastline of the Tyrrhenian and Ligurian Seas. At kilometer marker 634.500, within the Municipality of Cervo in the province of Imperia (IM), the highway passes near the "Tana dei Colombi" condominium. This area is also notable for the planned Tyrrhenian cycle route, which is set to utilize the former railway site adjacent to the coastline.

Figure 3.1 Map of Case Study of Cervo, Province of Imperia(IM)

3.1.1 Geographical Location

Our case study is focused on a location near Via Aurelia, in which a double story house who is facing the erosion process near the edge of the cliff. (Refer Figure 3.1.1.1).

Due to the high erosion and decaying of notch depth, the risk of landslides in this area posed a serious threat to human life. Therefore, it was necessary to investigate the slope stability and forecast the upcoming landslide in order to ensure the safety of those traveling through this route.

Figure 3.1.1.1 Site view of Case Study affected area(Scarpati,2023)

Cervo is surrounded by steep alpine slopes and rocky formations, places it in a geologically active zone. The proximity to the Alps, combined with the effects of weathering, erosion, and natural watercourses, makes managing the risk of rock falls a key concern for the town's infrastructure and residents.

3.1.2 Historical Significance

Cervo has a long history that goes back to prehistoric times. The village's name originates from the Latin phrase "cervus," which means deer, presumably because deer were present in the surrounding woodlands in ancient times.

The SS1 "Aurelia" traces its origins to the ancient Roman consular road, the Via Aurelia, established to connect Rome with the northern territories. Over centuries, it has remained a crucial artery for trade, travel, and cultural exchange along Italy's western coast. The Municipality of Cervo itself is steeped in history, with medieval architecture, narrow cobblestone streets, and historic landmarks. The transformation of the former railway site into the Tyrrhenian cycle route reflects a modern initiative to promote sustainable tourism while preserving and repurposing historical infrastructure. Following are the famous nearby attractions:

- **Historical Centre:** Cervo's lovely historical center, with cobblestone lanes, antique stone homes, and charming squares, sits at the heart of town. The village's medieval structures and a 17th-century fortification contribute to its historical atmosphere.
- **The Cervo Cathedral:** The church, also known as St. John the Baptist, is a noteworthy feature in the community. The cathedral has a magnificent baroque front and exquisite interiors, with paintings and artworks.
- **Beaches:** Cervo has beautiful sandy beaches and crystal-clear seas, making it a great location for beach lovers. Visitors may enjoy sunbathing, swimming, and water-related activities along the gorgeous shore.

3.1.3 Case Study Setting

The lithological nature of the rock mass (flysch), consisting of an alternation of calcareous-marly (tough), arenaceous (tough) and clayey layers (tender), creates erratic erosion, with the formation of cavities and inlets (refer Figure: 3.1.3.1), where the softer clay lithotypes are removed from the wave motion), and overhanging rocky banks where the most tenacious lithotypes resist greater resistance to wave energy.

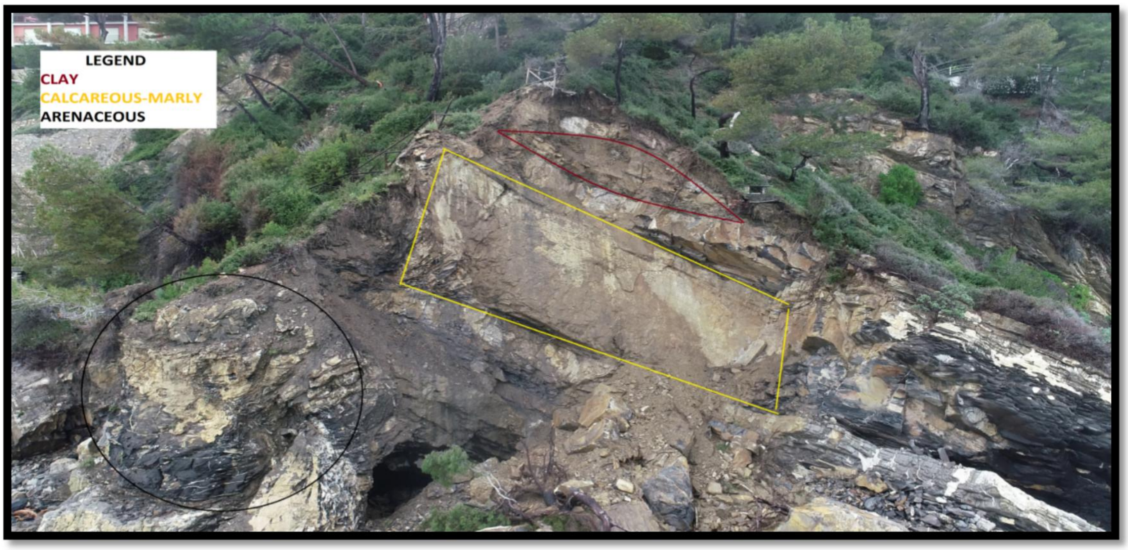

Figure 3.1.3.1 Layer formation (Scarpati,2024)

The progressive undermining of the foot of the rocky front favors, during intense and prolonged rain events, the triggering of landslides which over the years produce a progressive decline morphology of the edge of the slope, which is now about 30 meters from the building condominium.

An example of this are the landslides that have occurred in recent years, and in particular the last two landslides which occurred in November 2023 and March 2024 (Refer Figure: 3.1.3.2 & Figure 3.1.3.3) respectively.

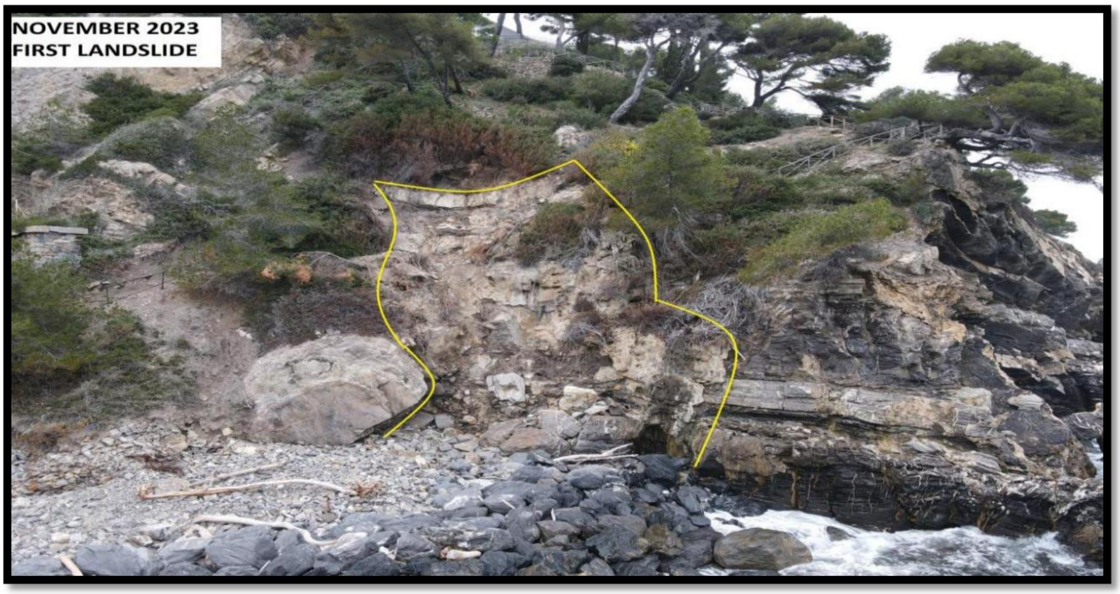

Figure 3.1.3.2 Marked first landslide occurred in November 2023 (Scarpati,2023)

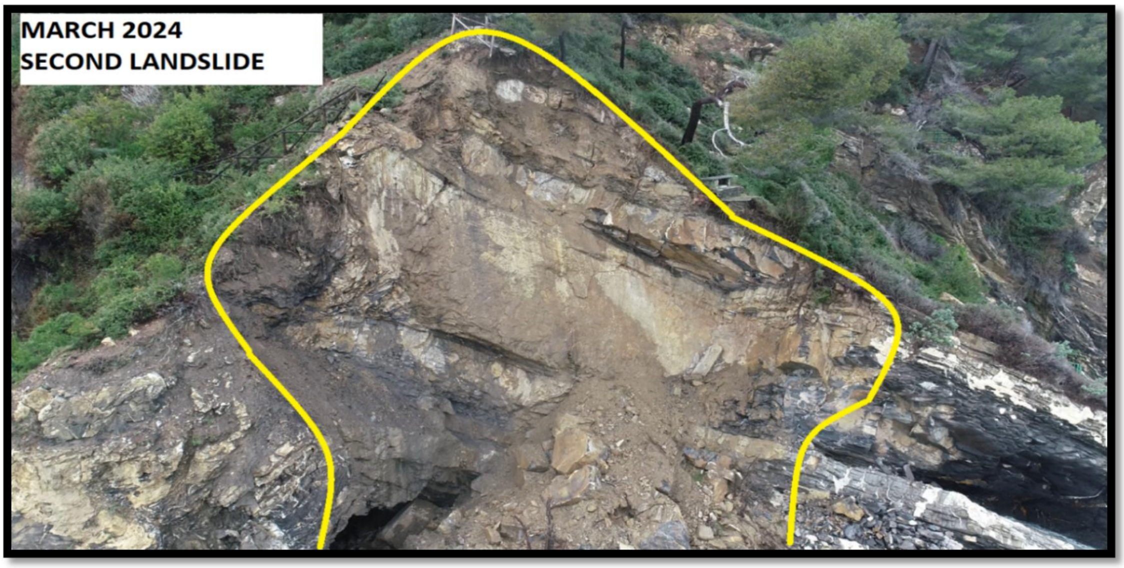

Figure 3.1.3.3 Marked second landslide occurred in March 2024 (Scarpati,2024)

At present, some situations of instability are also evident potential that could affect the rock face during the upcoming storm surges and/or rain events and further retreat the edge of the rocky front: in particular, the photograph in (Figure 3.1.3.4) highlights a mass strongly altered and cracked rock upstream in the last area failure (March 2024).

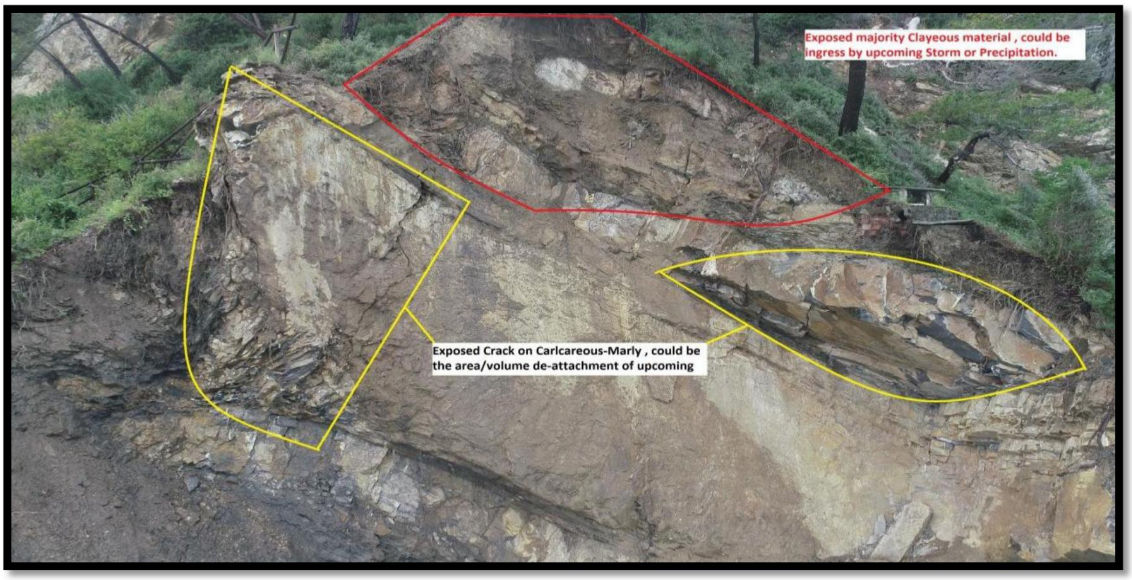

Figure 3.1.3.4 Causes for Upcoming Landslide.(Scarpati,2024)

The condominium building is not currently in dangerous conditions, but without consolidation and safety precaution the slope may become more dangerous in future.

In the same way, the underlying site of the future Tyrrhenian cycle route on the former railway site, in section in the tunnel and close to the landslide area, could be at risk in the near future.
The necessary consolidation and safety measures for the slope, (cortical strengthening using reinforced nets, have to be in any case accompanied by appropriate intervention to protect the coast from wave motion: in fact, without one adequate protection of the rocky front at sea any intervention to stabilize the slope would be nullified from the effects of the first intense storm.

3.2 Methodological Approach

The methodology adopted for analyzing the coastal cliff stability in the selected case study. Provides numerical analyses. In particular, the effect of the progressive erosion of the sea at the toe of the cliff is studied.

Numerical modeling plays a crucial role in understanding slope stability, especially in coastal environments where erosion processes continuously alter the geomorphology. RS2 (Finite Element Method – FEM Analysis) was selected due to its ability to simulate progressive failure, material plasticity, stress-strain relationships, and groundwater interaction, which are essential for analyzing the stability of the erosive sea cliff along the SS1 "Aurelia" in Cervo. The numerical model allows for both elastic and plastic behavior to be considered, providing a comprehensive understanding of failure mechanisms under different loading conditions.

Figure 3.1.3.1 provides a broad view of the sequential steps of the methodological. Starting from the Site Geophysical and photographic data, the first step is to decompose and represent data which were concluded in Adobe Illustrator. After investigating the results, the most critical line of section is selected which involves already the landslide occurred on March 2024. (Refer Figure 3.1.3.2)

The second step is to cut the section in desired position from the Digital Terrain Model(DTM) by importing. Import DTM of area in QGIS software, which combine the DTM and Google Earth to have orthophoto, under the WGS-84 co-ordinate system. After that, section is composed using the Terrain Profile command which is exported in (.dxf) format to AutoCAD.

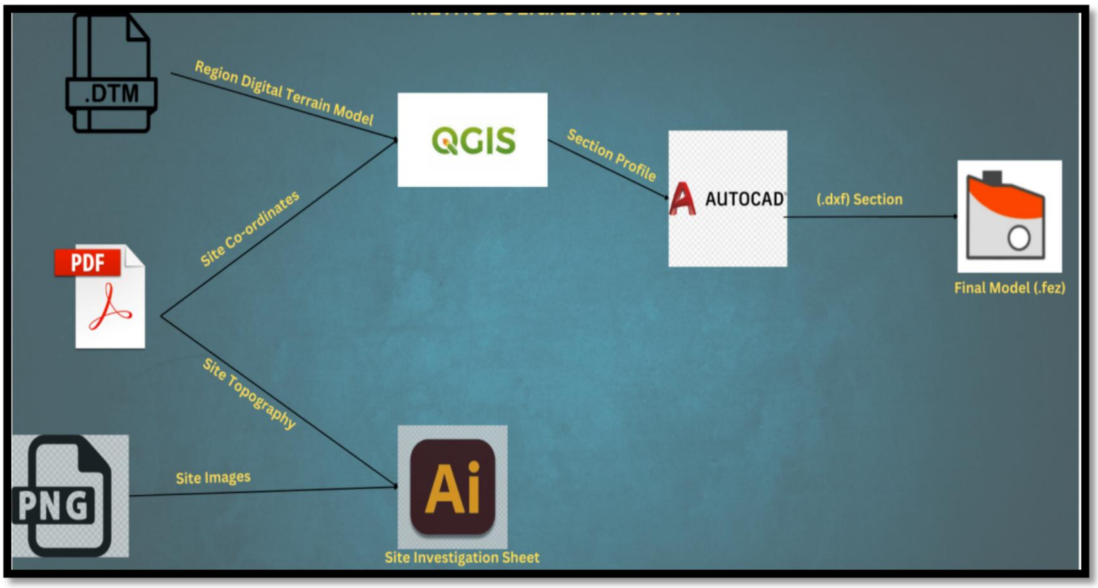

Figure 3.1.3.1 Methodological Approach for Numerical Analysis

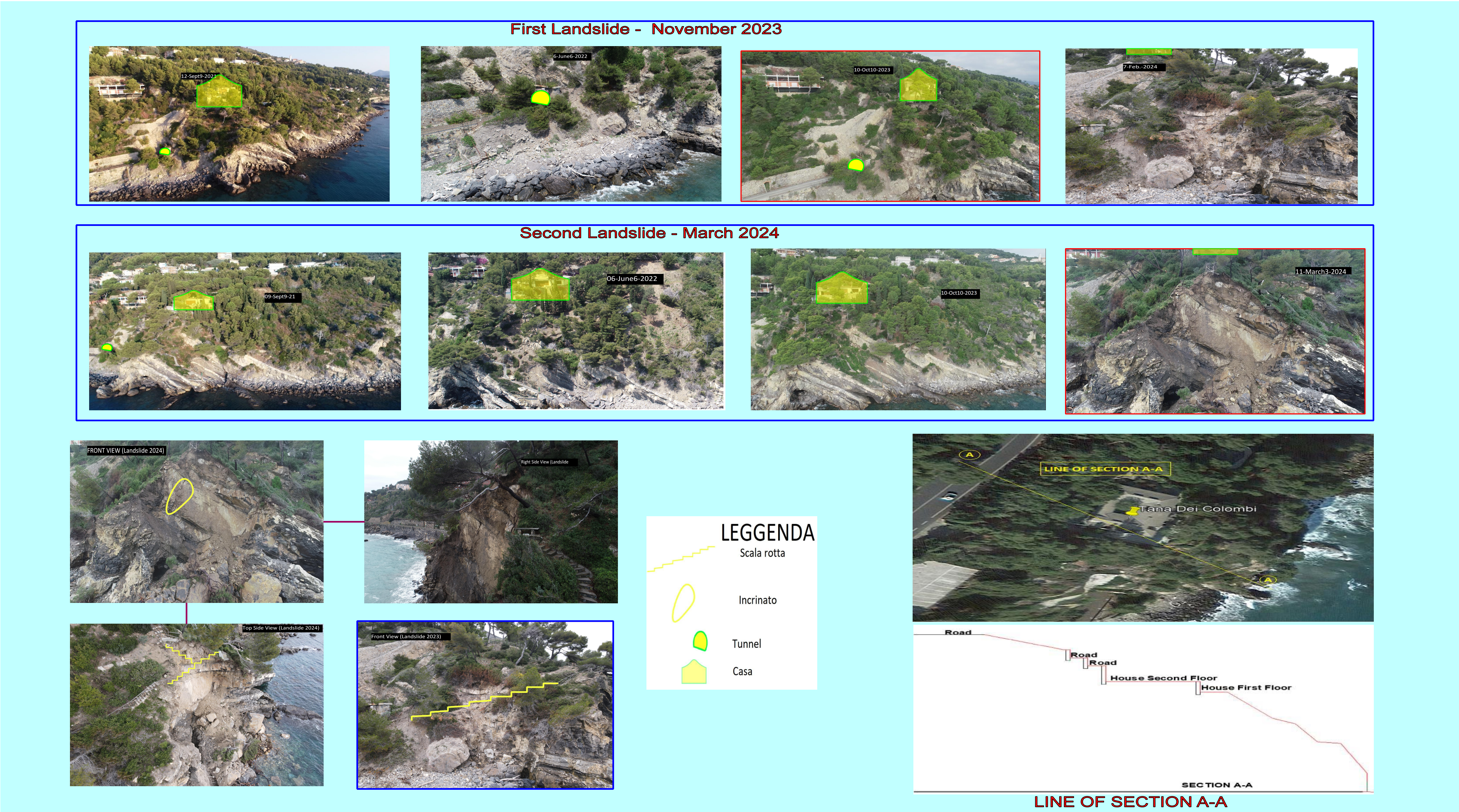

Figure 3.1.3.2 Site Landslide Tracking for over 4 years' time frame w-e-f 2021

The third Step is the planning phase for RS2 which is performed in AutoCAD,30 stages of excavation is imported to RS2 for analysis. The numerical model in RS2 encompasses,31 stages: the 1st stage for Initial Composition ,2nd to 25th stages for excavation, and creation of the profile, 31st for loading (simulation of the buildings weight).

3.2.1 Analysis of the Existing Data

Accurate site data is essential for constructing a reliable numerical model and understanding the long-term behavior of the coastal cliff. The dataset used for this study includes a Geological surveys (Report), a Digital Terrain Model (DTM), and four years of photographic evidence documenting cliff decay. This section discusses how these data sources were utilized to assess the cliff's stability and validate the numerical model.

Dott. Alessandro Scarpati conducted a detailed site survey, providing critical information on the stratigraphy, lithology, and structural discontinuities of the cliff. The report also includes data on the mechanical properties of rock and soil, fault lines, and zones of weakness that could contribute to slope instability. This information was used to refine the input parameters for the RS2 model, ensuring that the numerical simulation accurately reflects real-world conditions.

The Digital Terrain Model was generated using high-resolution LiDAR and photogrammetry techniques, capturing the topography of the cliff and surrounding area. The DTM provided valuable insights into elevation changes, slope angles, and surface irregularities, which were integrated into the QGIS application for extraction of critical section profile.

A chronological four-year photographic dataset was analyzed to track the progression of coastal erosion and cliff retreat. The images highlight significant events such as rock falls, undercutting, and slope failures, offering a visual record of changes over time. This evidence was compared with numerical simulation results to validate the predicted erosion patterns and refine the model's accuracy plus help to predict the future failure.

3.2.2 Formation of Section Profile

This process involved several key steps to ensure precision and compatibility with numerical modeling software. (Figure 3.2.2.1)

First, the DTM of the study area was imported into QGIS software, which facilitated the integration of the DTM with Google Earth imagery, allowing for the generation of an orthophoto under the WGS-84 coordinate system. This step ensured accurate georeferencing and spatial consistency.

Next, the Terrain Profile command in QGIS was used to extract the desired section from the DTM. This section was then exported in .dxf format for further refinement in AutoCAD, where necessary adjustments were made to ensure the profile accurately represents the existing topographical conditions. Initially, it was considered the section will start from house end till the notch depth (Refer Figure 3.2.2.1)

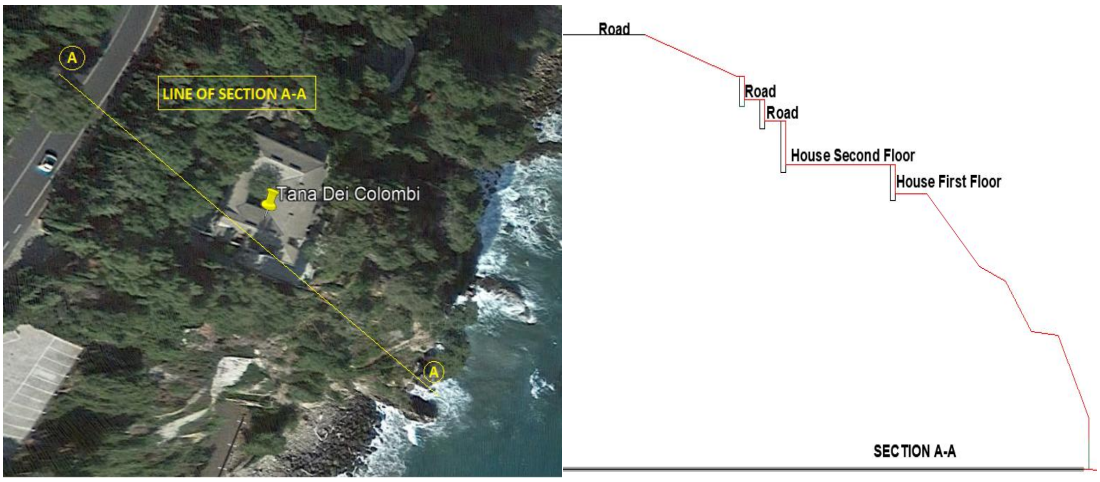

Figure 3.2.2.1 Line of Section & Section A-A considered for analysis

After exporting the section profile in .dxf format from QGIS, further modifications were carried out in AutoCAD to ensure accuracy and suitability for numerical analysis. To enhance the precision of the model, site photographs and investigation sheets were analyzed to trace the formation of geological layers, identify notch depths, and locate visible cracks within the cliff face. This information's were integrated into the section profile, ensuring that the numerical model reflects real-world conditions more accurately. (Refer Figure 3.2.2.2)

Additionally, to simulate the progressive formation of the slope profile over time, the section was divided into 30 different stages. This staged approach allows for a more realistic assessment of slope stability over time, ensuring that the numerical model in RS2 effectively captures the evolution of stress distribution, deformation patterns, and failure mechanisms.

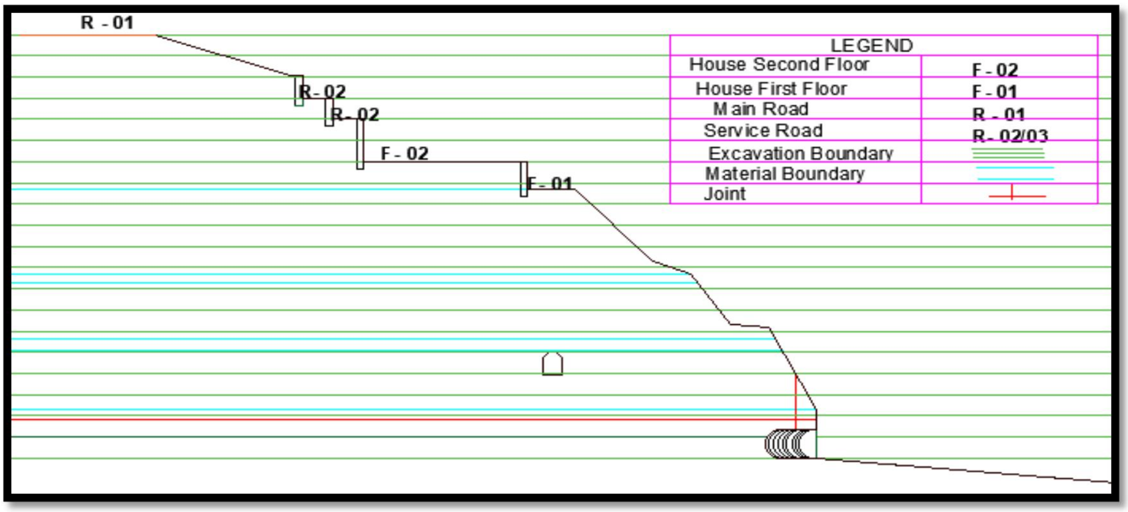

Figure 3.2.2.2 Updated section with multiple layers

3.3 Numerical Model and Back Analysis

The first step of the numerical study was the back-analysis. The studied slope was represented as before the occurrence of the landslide on March 2024, with the aim to simulate correctly that event. This procedure is necessary to validate the numerical model in order to be correctly used for forecasting purposes.

RS2 is a Finite Element Code from Rocscience commonly used to model and analyze geotechnical structures for civil and mining application, by implementing the Finite Element Method.

The finite element method is a computational approach to solving partial differential equations in engineering and applied research. The region of interest is divided into small, finite portions of basic shapes known as finite elements. These components, linked together by common nodes, discretize the continuum and form the mesh. Interpolation functions, such as polynomial functions, are then employed to interpolate the field variables (i.e., stress and displacements) over the element.

The FEM methodology offers an advantage over the limit equilibrium method (LEM) for slope stability analysis since it does not need making assumptions about the form and position of the failure surface in advance. Furthermore, the analysis may be done in both elastic and plastic circumstances, and the strain process can be tracked (to represent progressive failure).

3.3.1 Layer Assignment and Properties

In RS2 (Rocscience), layer assignment is crucial for accurately defining the geotechnical conditions, failure mechanisms, and material interactions within a slope or excavation model. The different types of boundaries like Material, Stage, Joint, Excavation, External serve distinct purposes in the numerical simulation. While preparing the section profile in Auto-CAD each separate layer is defined for one boundary type, in order to have better functionality and resist the emerging effect between boundary types. (Refer Figure 3.3.1.1)

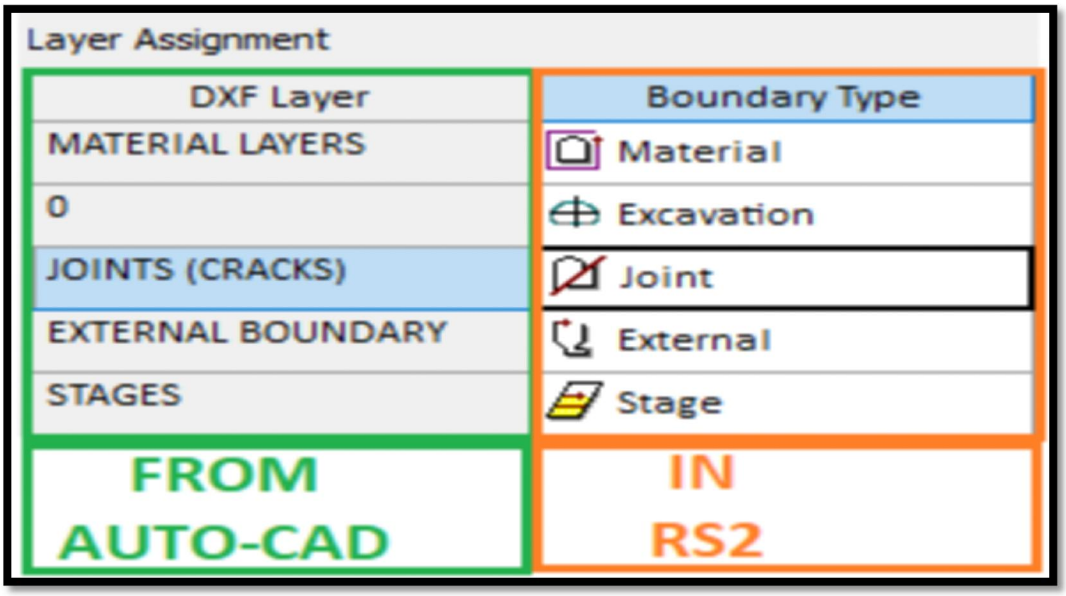

Figure 3.3.1.1 Conversion of .dxf (AutoCAD) layers into Boundary (RS2)

3.3.2 Material Boundary

Define the amount and spacing of different soil and rock strata inside the model. These boundaries guarantee that each material region receives the appropriate mechanical and strength characteristics, such as cohesion, friction angle, Young's modulus, and Poisson's ratio (Table 1). In geotechnical modeling, material borders are particularly relevant in stratified terrains where differential material properties impact stability and deformation. In our case study model, material boundaries delineate the transition between Arenaceous and Calcareous-Marly layers, capturing the different erosion and failure behaviors of these materials. Properly defining material boundaries allows for an accurate representation of the subsurface structure and load-bearing capacity of the soil and rock mass.

Important Point is the dual nature of both materials in terms of plasticity which is define in such a way that initially the whole section is considered as Elastic but as soon as the excavation started each layer by layer becomes the Plastic in order to functionalize the dual behavior of material in numerical analysis.

Table 1 Initial material properties of Arenaceous & Calcareous Marly

MATERIAL PROPERTIES				
S .No	ARENACEOUS		CALCAREOUS-MARLY	
01	Unit Weight	26.5 kN/m3	Unit Weight	22 kN/m3
02	Poisson's Ratio	0.4	Poisson's Ratio	0.4
03	Young Modulus	5x106 kPa	Young Modulus	5x106 kPa
PEAK STRENGTH				
04	Cohesion	2400 kPa	Cohesion	1300 kPa
05	Tensile Strength	1000 kPa	Tensile Strength	500 kPa
06	Friction Angle	37°	Friction Angle	35°
RESIDUAL STRENGTH				
07	Cohesion	300 kPa	Cohesion	150 kPa
08	Tensile Strength	300 kPa	Tensile Strength	125 kPa
09	Friction Angle	35°	Friction Angle	33°

3.3.3 Stage Boundary

Used to represent excavation sequences, continuous erosion, or building phases by separating the model into several stages of material removal and reinforcement. These stages are crucial. In our case study, 32 stage boundaries are applied to simulate stepwise excavation, loading and initial properties selection. Stages are as: one stage for the initialization of the model; 21 stages for creating the slope profile by means of the progressive removal of 3-meter depth layers except the depth notch of 8.250 meter, for 9 stages of different depth (Max: 2m, Min: 0.5m) are randomly repeated; second last stage is dedicated for tunnel excavation; one last stage for applying the loadings due to the buildings. The ability to control staged excavation ensures that the model reflects real-world failure mechanisms and stabilization efforts. (Refer Figure 3.3.3.1)

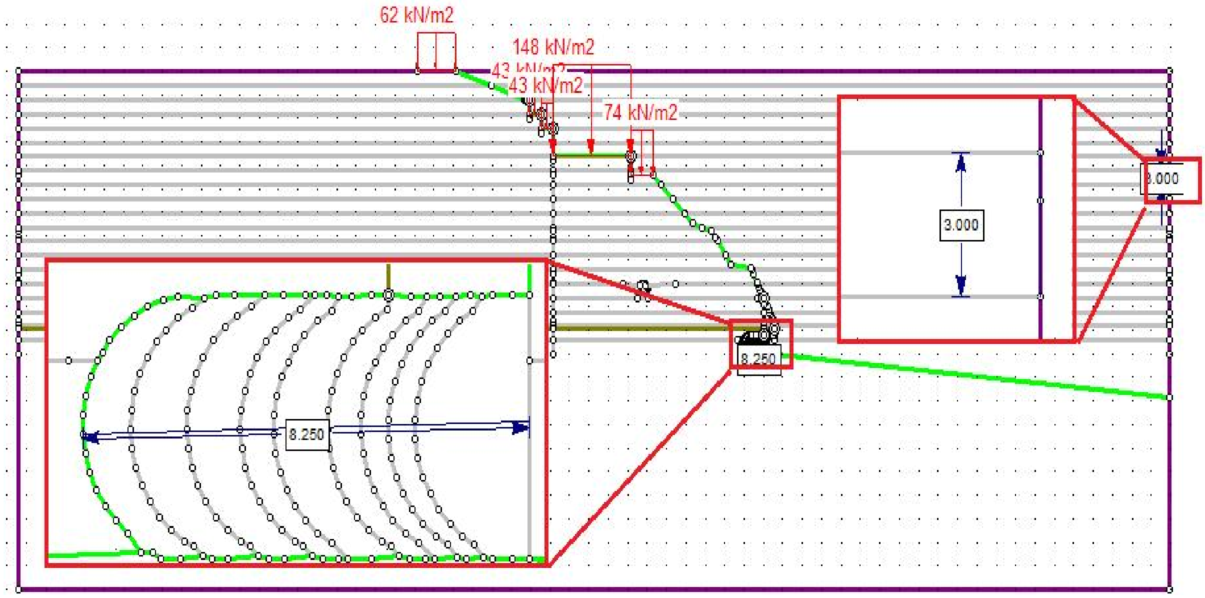

Figure 3.3.3.1 Stage boundary width for Notch-depth & Excavation

3.3.4 Joint Boundary & Network

Joint boundaries reflect structural discontinuities in the rock mass, such as fractures, bedding planes, faults, or shear zones. These limits are crucial in delineating weak planes where material may break or slide, severely influencing the overall stability of a slope or excavation.

Initially in this case study, joint boundaries help model pre-existing cracks and fractures that contribute to progressive cliff failure: we considered 2 pre-existing cracks joints (1 vertical of 8 meter and 1 Horizontal of 194.830 meter). Other important parameter is about Joint end conditions in which the exposed joints ends are considered open, while the embedded are closed end condition. The interaction between joint boundaries and material properties determines the likelihood of block detachment, shear failure, or sliding along discontinuities. (Refer Figure 3.3.4.1). The mechanical parameters assumed for the joint are reported in Table 2.

Table 2 Selected properties of joint

JOINT PROPERTIES		
S.NO	**TYPE**	**DATA**
01	Slip Criterion	Mohr-Coulomb
02	Peak Friction Angle	37°
03	Peak Cohesion	0
04	Tensile Strength	0
05	Normal Stiffness	$3.7\text{x}10^6$ (kPa/m)
06	Shear Stiffness	$1.3\text{x}10^6$ (kPa/m)

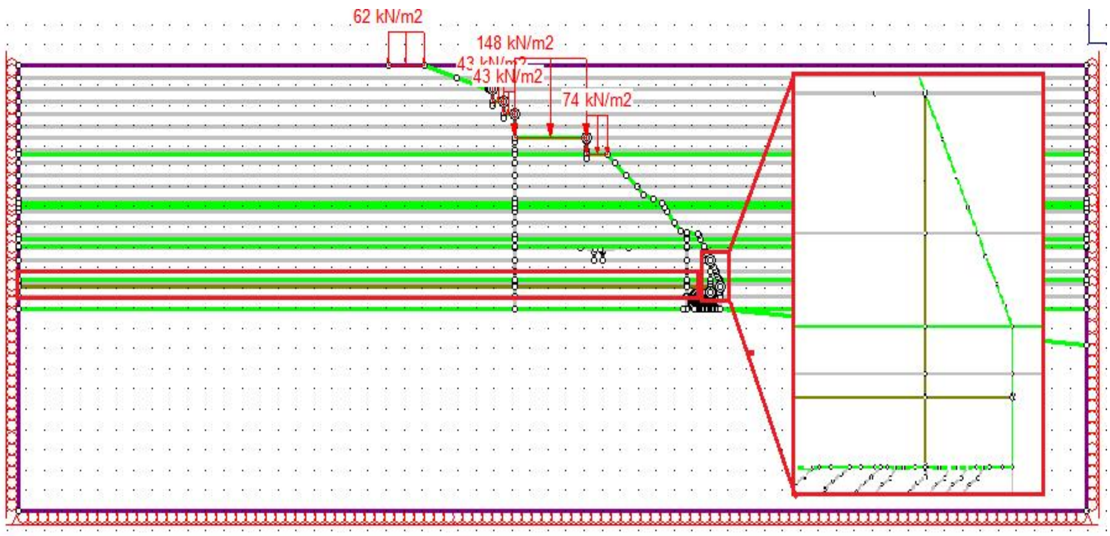

Figure 3.3.4.1 Highlights Joints & magnify the vertical joint along with dimensions

After that, by deeply investigating the photographic evidence around 7 cracks(Joints) of 6 meter of spacing (Min:5m & Max:9m) with standard deviation of 1 meter were found between the notch depth-end and the house. For further detailing (Refer Figure 3.1.3.2)

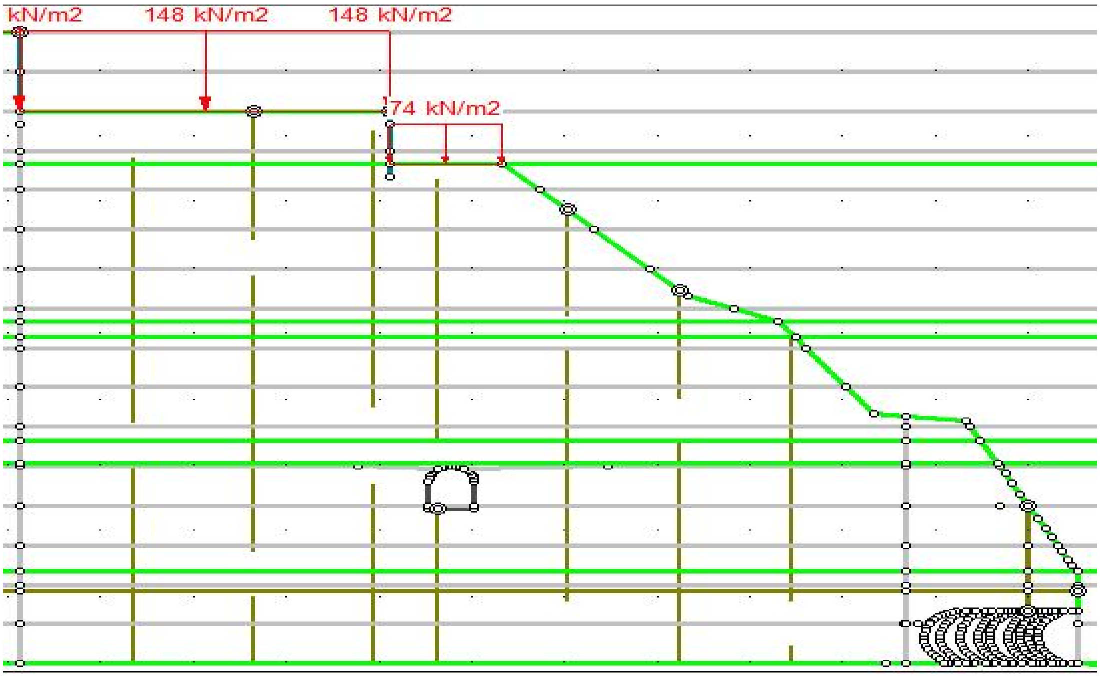

Figure 3.3.4.2 Desired Area b/w house & notch end for Joints Network

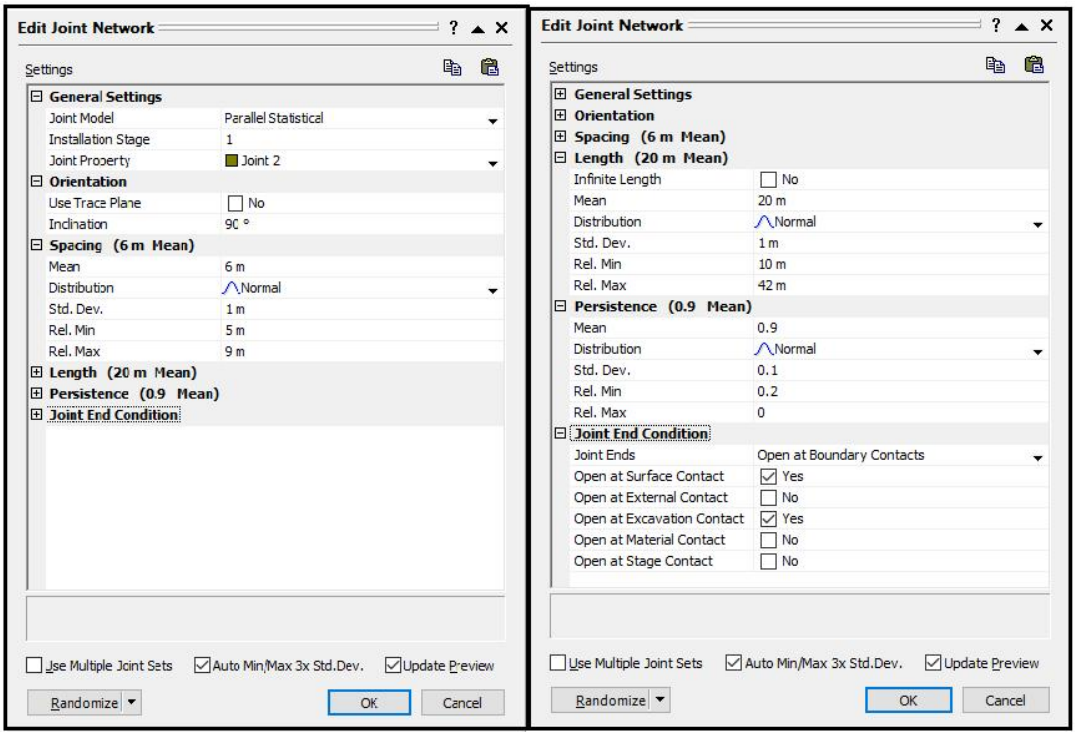

Figure 3.3.4.3 Selected properties of Joint Network

3.3.5 External Boundaries

The exterior boundary in RS2 specifies the numerical model's overall domain, which encloses the geotechnical systems to enable correct distribution of stresses and realistic simulations. It is vital for imposing boundary conditions, avoiding numerical instabilities, and ensuring computing efficiency. In this case at the bottom of the model the displacements in all directions have been avoided, at the lateral boundaries the vertical movement has been allowed while preventing horizontal ones. This boundary configuration ensures the stability of the model and accurately represents real-world constraints in slope stability analysis.

In this case study, the dimensions of the model were carefully selected to encompass the full extent of the slope failure mechanism while avoiding excessive computational demand. To avoid boundary-induced stress reflections, the model was expanded laterally outside the possible failure zone, and the vertical depth was altered to account for underlying stable layers. These requirements ensure that the numerical analysis produces realistic findings while retaining stability and efficiency in calculations.

(Refer Figure 3.3.5.1)

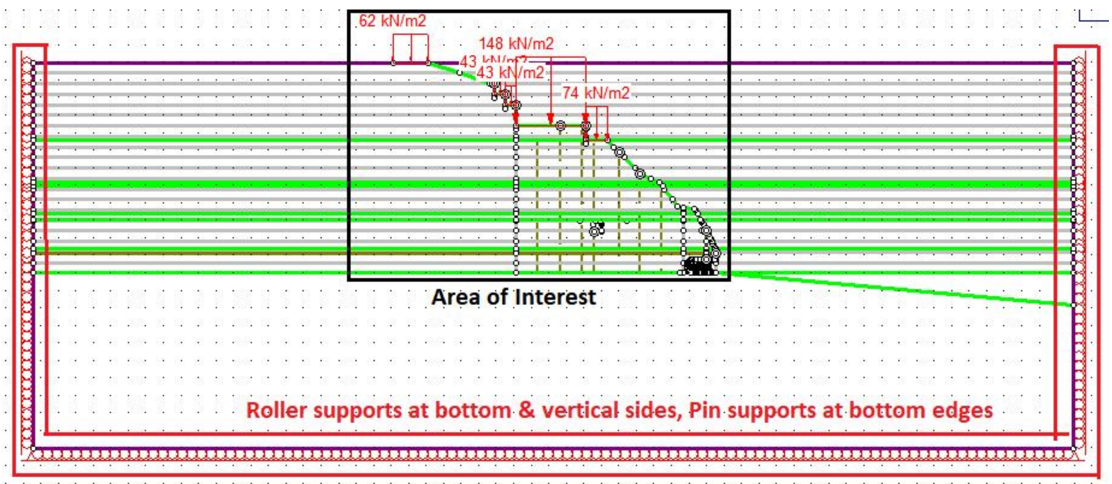

Figure 3.3.5.1 Highlighted the Area of Interest and the boundary constrains

3.3.6 Loading

For a 2-story house with old construction techniques and heavy materials, the dead load is significantly higher than typical modern buildings. The live load remains within expected ranges for residential buildings.

Table 3 Calculation for First Floor

S.No	TYPE	DATA
DEAD LOAD (G.1)		
01	External Walls	30 kN/m^2
02	Internal Walls	15 kN/m^2
03	Roof Dead Load	2.5 kN/m^2
04	Floor Dead Load	11 kN/m^2
05	Other Permanent Loads (Stairs,Fixtures)	5 kN/m^2
Total Dead Load (G.1)		**63.5 kN/m^2**
LIVE LOAD (Q.1)		
01	Living Areas (Bedrooms,Living Rooms etc.)	2 kN/m^2
02	Storage Areas	4 kN/m^2
03	Corridor and Hallways	2 kN/m^2
04	Stairs	3.5 kN/m^2
Total Live Load (Q.1)		**11.5 kN/m^2**
TOTAL LOADS for FIRST FLOOR (G.1+Q.1)		**74 kN/m^2**

Table 4 Calculation for Second Floor

S.No	TYPE	DATA
DEAD LOAD (G.2)		
01	External Walls	60 kN/m^2
02	Internal Walls	30 kN/m^2
03	Roof Dead Load	5 kN/m^2
04	Floor Dead Load	22 kN/m^2
05	Other Permanent Loads (Stairs, Fixtures)	10 kN/m^2
Total Dead Load (G.2)		**125 kN/m^2**

LIVE LOAD (Q.2)		
01	Living Areas (Bedrooms, Living Rooms etc.)	4 kN/m^2
02	Storage Areas	8 kN/m^2
03	Corridor and Hallways	4 kN/m^2
04	Stairs	7 kN/m^2
Total Live Load (Q.1)		**23 kN/m^2**
TOTAL LOADS for FIRST FLOOR (G.2+Q.2)		**148 kN/m^2**

3.3.7 Mesh Creation

The mesh formation process in RS2 involves defining the element type and distribution across the model domain. In this case a Uniform Mesh to ensure an even distribution of elements throughout the model, preventing areas of excessive refinement that could affect numerical stability. The selected Element Type was a 6-Noded Triangle, which provides greater accuracy in stress analysis compared to simpler elements like 3-noded triangles. These higher-order triangular elements allow for a smoother representation of stress gradients within the rock and soil materials, improving the reliability of the simulation. (Refer Figure: 3.3.7.1)

A well-structured mesh is essential for getting accurate results and ensuring that the model converges correctly. A fine mesh enhances precision but lengthens computing time, whereas a coarser mesh decreases processing requirements but may introduce mistakes or oversimplification. The Uniform 6-Noded Triangular Mesh in this model helped capture localized deformations and stress concentrations effectively, especially in areas prone to failure such as the cliff face and excavation zones.

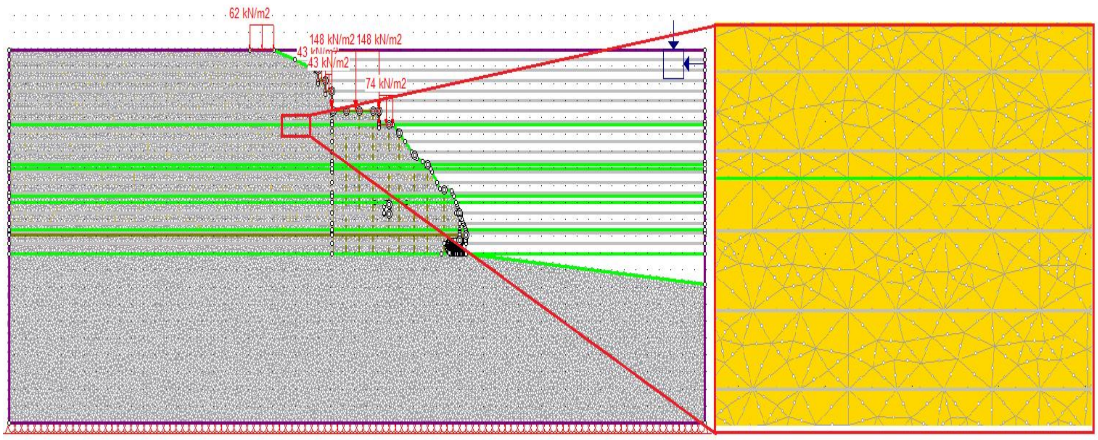

Figure 3.3.7.1 Mesh applied on section & magnify view of 6-Noded Triangle

4 Back Analysis & Forecasting

4.1 Back Analysis for Model Validation

Back analysis is a retrospective method used in geotechnical design to comprehend past slope failures and improve numerical models for future forecasts. Back analysis, which incorporates documented failures, material qualities, and ambient circumstances, helps confirm theoretical assumptions and increase the accuracy of stability assessments.

Back analysis is more than just matching previous occurrences; it also involves learning from differences between observed and predicted results. These inconsistencies may reveal limits in our present understanding or data gaps. By thoroughly studying these variations, researchers may update their models and enhance forecast accuracy for future events.

In this study, the back analysis is performed using Rocscience RS2. Given the dynamic nature of coastal erosion, this analysis aims to identify the key failure mechanisms, validate material parameters, and assess the long-term behavior of the slope under natural and anthropogenic influences.

The analysis conducted in this thesis focuses on a specific site that has experienced past slope failure events. Before beginning the simulation of the recent event, it is important to accurately determine key parameters such as material properties, mesh formation, boundary-conditions, loading conditions, constitutive behavior, joints structure, which can be challenging.

4.1.1 Formation of Pre & Post Failure Section

Using QGIS and the Digital Terrain Model (DTM) of 2017, extracted the pre-failure section of the coastal cliff to establish the baseline topography of the study area. A landslide occurred in March 2024 within the same section, significantly altering the cliff profile. To analyze this failure, utilized photographic evidences taken before and after the event to identify the detached block that collapsed during the landslide. By carefully tracing the extent of material displacement, reconstructed the post-failure section. This allowed for a comparative analysis between the 2017 (pre-failure) and 2024 (post-failure) profiles, forming the basis for back analysis. Through this comparison, was able to assess the stability conditions leading to the failure and refine the input parameters for numerical modeling in RS2.

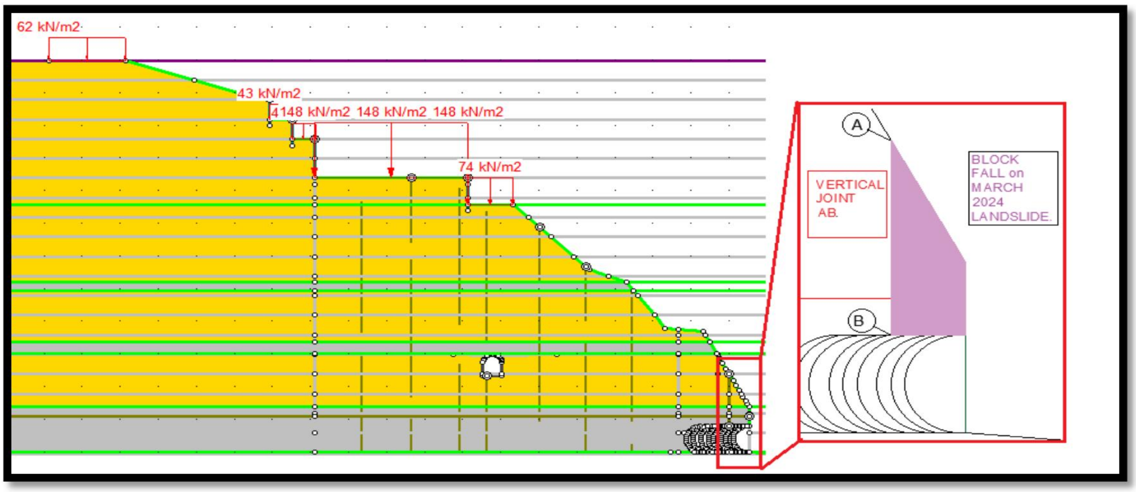

Figure 4.1.1.1 Pre-Failure Section extracted from QGIS via Digital Terrain Model of (2017).

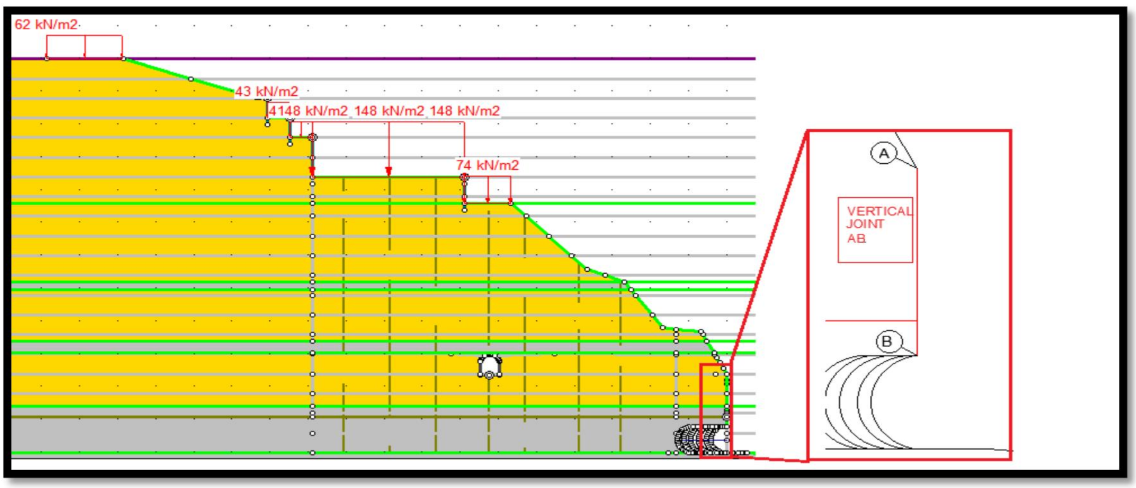

Figure 4.1.1.2 Post-Failure Section after observing photographs and pre-failure section.

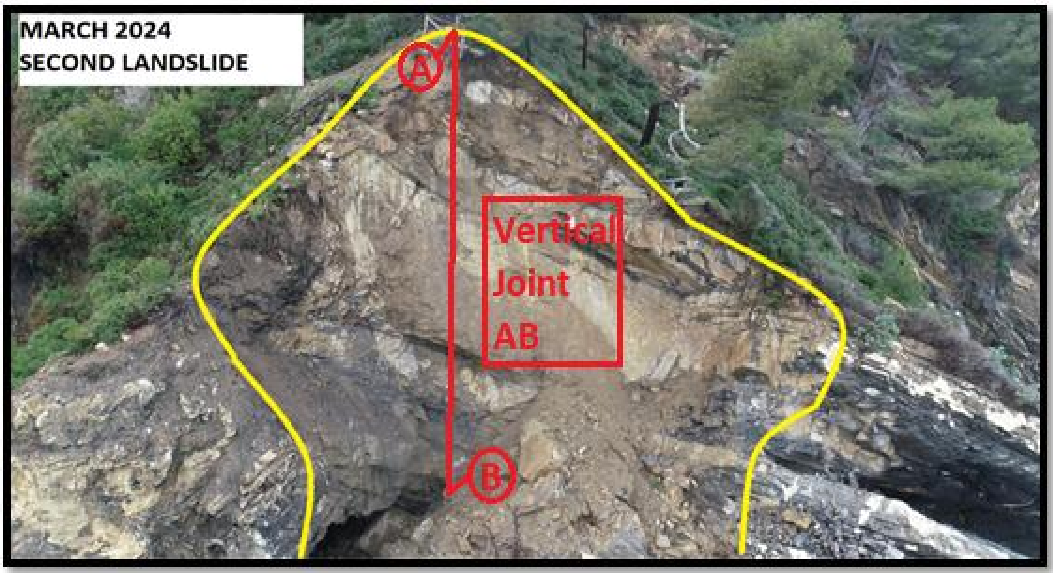

Figure 4.1.1.3 Photo of 2024 Landslide Block (Scarpati,2024)

Figure 4.1.1.4 Photo before March 2024 landslide (Scarpati ,2024)

4.1.2 Initial Parameter Selection

After the formation of the section, the next step involves assigning fixed parameters essential for the back analysis. These parameters include the applied load from the house and the road, tunnel excavation as its positioned between notch and house, as well as the joint properties within the cliff structure. The applied loads account for the structural influence on slope stability, while joint properties define the mechanical behavior of discontinuities within the rock mass. Establishing these fixed parameters ensures that subsequent iterations focus on refining the material properties to accurately replicate the observed failure conditions. The material properties used are collected in below table 5.

Table 5 Different material properties for iterative process

Material Properties							
S.No	**Tensile Strength (kPa)**		**Friction Angle (Degree)**		**Cohesion (kPa)**		**S.R.F**
#	**(AREN)(Residual)**	**(CALC)(Residual)**	**(AREN)(Residual)**	**(CALC)(Residual)**	**(AREN)(Residual)**	**(CALC)(Residual)**	**#**
1	460	150	37	35	1010	710	0.60
2	450	180	37	35	1100	720	0.71
3	400	150	37	35	900	500	0.72
4	500	200	37	35	1100	750	0.77
5	450	140	37	35	1000	700	0.86
6	480	230	37	35	1280	780	1
7	450	230	37	35	1200	780	1.1
8	460	210	37	35	1260	760	1.3
9	500	250	37	35	1300	800	1.05
10	465	185	37	35	1140	740	0.88
11	490	200	37	35	1200	760	0.95
12	**500**	**200**	**37**	**35**	**1200**	**800**	**0.99**

4.1.3 Assigning Material Properties

The next step involved assigning material properties to the two primary formations in the study area: Arenaceous and Calcareous-Marly. To ensure consistency in the analysis, the peak strength properties of both materials were kept constant while systematically adjusting the residual strength parameters. This iterative approach allowed for gradual refinement, where the residual properties were modified step by step until the model accurately reflected the observed failure in terms of Strength Reduction Factor (S.R.F), appeared of Yield element at landslide block. By simply comparing the numerical results with real-world conditions.

4.1.4 Results

A useful tool for the back analysis was the Strength Reduction Factor (SRF). The SRF is a numerical indicator used to determine the stability of a slope, where an SRF value below 1 signifies failure. The strength parameters were automatically adjusted until the SRF fell below this critical threshold, replicating the failure conditions of the March 2024 landslide. Achieving an SRF lower than 1 confirmed that the assigned material properties accurately represented the instability observed in the field, thus enhancing the reliability of the numerical model. (Refer Figure 4.1.4.1)

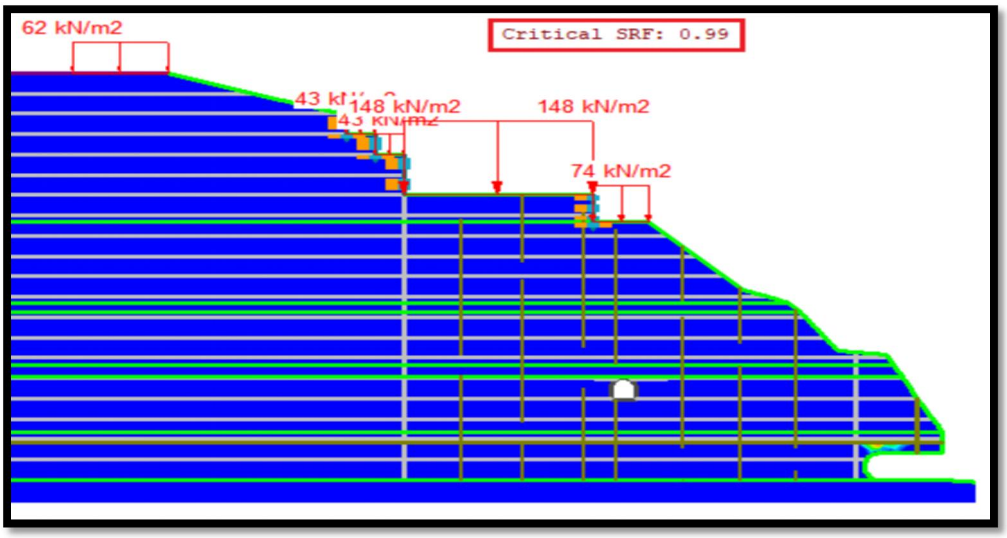

Figure 4.1.4.1 Critical S.R.F for Back Analysis

Another element to be checked for the valuation of the model is the yielded area of the slope in the RS2 model were predominantly concentrated near the detachment area of the cliff, which corresponds to the observed failure surface in the field. This concentration of yielded elements indicates that the material in this region exceeded its strength limit first, marking the initiation of failure. As the numerical model progressed, with shear and tensile stresses reaching critical thresholds. The proximity of these yielded elements to the detachment area aligns with the actual location of the landslide, confirming the accuracy of the model's representation of the failure mechanism. This localized concentration of failure near the detachment zone reflects the role of material properties and boundary conditions in triggering the landslide, and is crucial for understanding the dynamics of slope failure in this specific area. (Refer Figure 4.1.4.2)

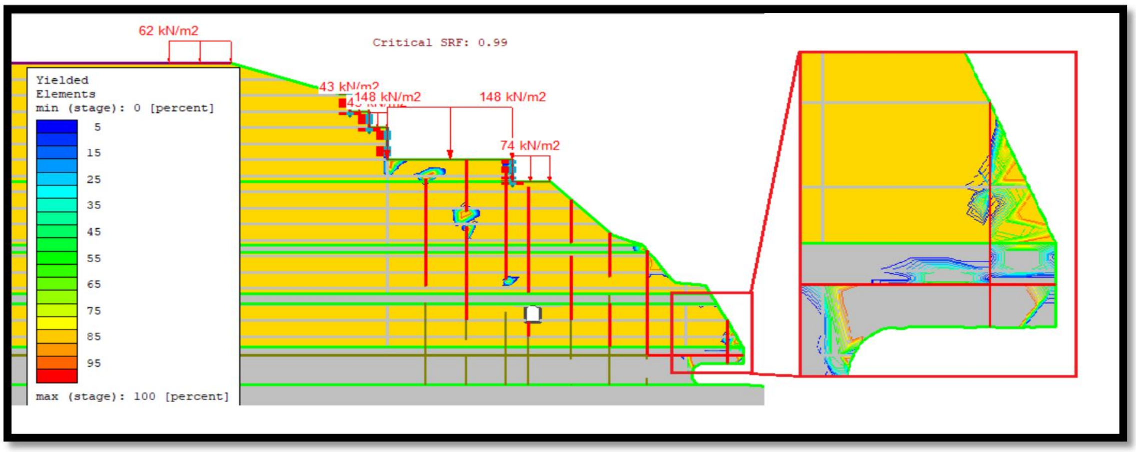

Figure 4.1.4.2 Appearance of Yield Element near the March 2024 Landslide

The failure surface predicted by the RS2 model showed a striking alignment with the actual displacement observed during the landslide event, reinforcing the validity of the numerical analysis. The model's failure surface, which developed as a result of the and the progressive accumulation of stress, mirrored the path and extent of the landslide observed in the field. The displacement patterns predicted by the model were consistent with the real-world deformation, both in terms of location and magnitude. This alignment between the modeled failure surface and the observed landslide displacement demonstrates the model's ability to replicate the physical behavior of the slope under similar conditions. It provides valuable insight into the mechanisms that triggered the failure, emphasizing the model’s reliability in forecasting similar events. (Refer Figure 4.1.4.3)

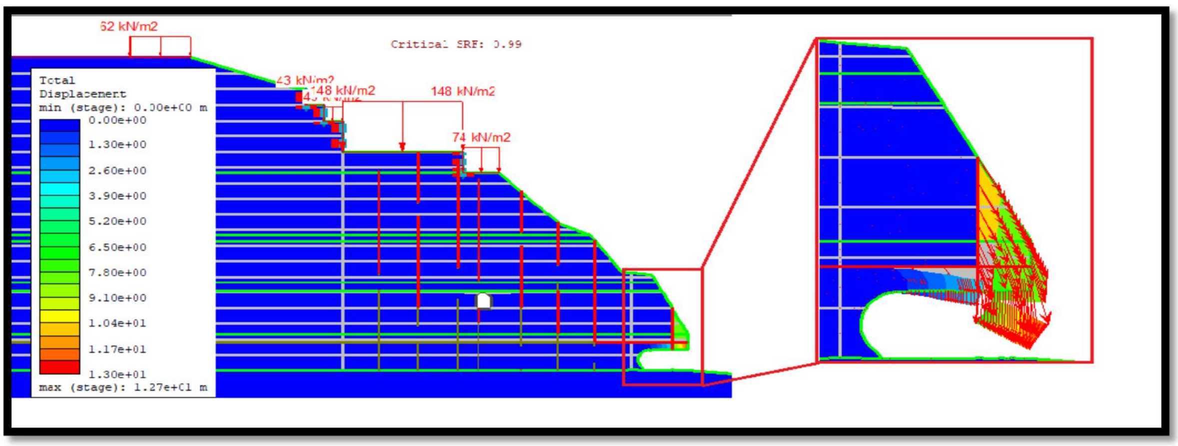

Figure 4.1.4.3 Total Displacement and Detachment of Block

4.2 Forecasting Analysis

Following the back analysis, which successfully replicated the March 2024 landslide event, the next step involved forecasting future failures along the decaying sea cliff. The primary objective of this phase was to predict potential instabilities that may arise due to continued erosion at the notch at the toe of the cliff. By utilizing the validated model in RS2, the forecasting analysis aimed to assess how the cliff might evolve under different conditions and determine the likelihood of future collapses.

Forecasting slope stability under different scenarios is essential for understanding how changes in geometry, such as notch depth and the uncertainty in the information about the structure of the cliff, can influence the likelihood of failure. In detail, the characteristics of the horizontal joint observed in correspondence of the failed rock volume are not known, in particular the persistence. For this reason, the two extreme conditions have been considered: the horizontal joint with persistence 100% and the absence of any horizontal joint. Regarding the notch, different depth has been considered, to simulate the erosion process over a long time. Three models with and without the horizontal joint, varying notch depths (6.5, 10, 14) were analyzed to evaluate their impact on slope stability. The results provide insights into the critical notch depths at which slope failure may occur and help inform design and mitigation strategies. (Refer Figure 4.1.4.1)

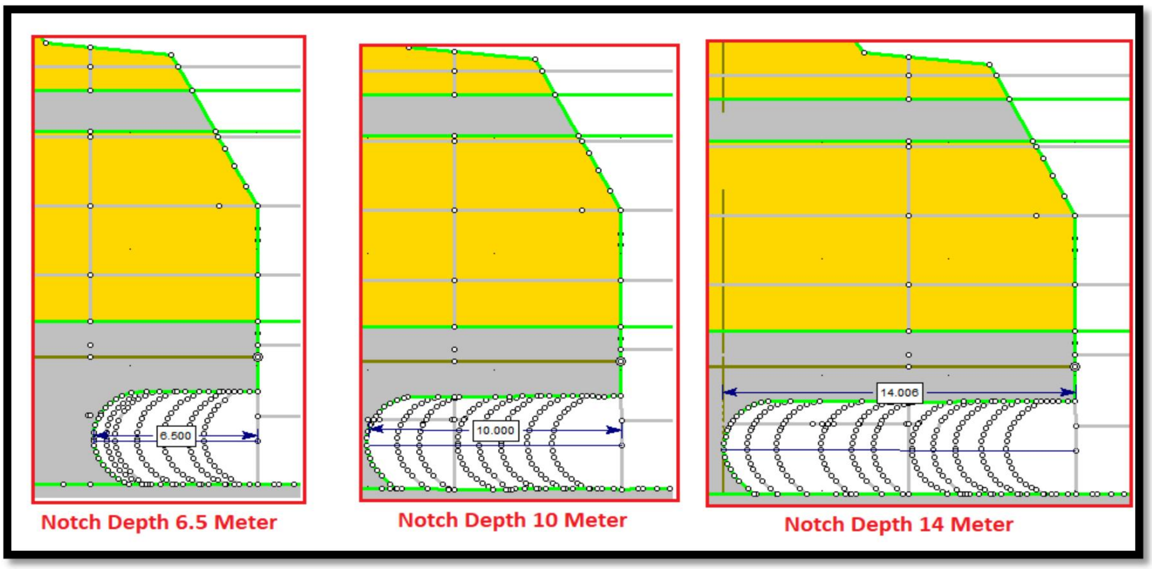

Figure 4.1.4.1 Three model with 3 different notch depth , with a persistent horizontal joint.

4.2.1 Methodology

The Shear Strength Reduction (SSR) method was employed in all the analyses to determine the Critical Strength Reduction Factor (SRF), while yielded elements, maximum plastic shear strain, total displacement was analyzed to identify potential failure mechanisms. The geometry for each model was derived from the calibrated back analysis model, ensuring consistency in material properties and boundary conditions, by removing the rock volume collapsed. The material properties used in the analysis are summarized in Table 6.

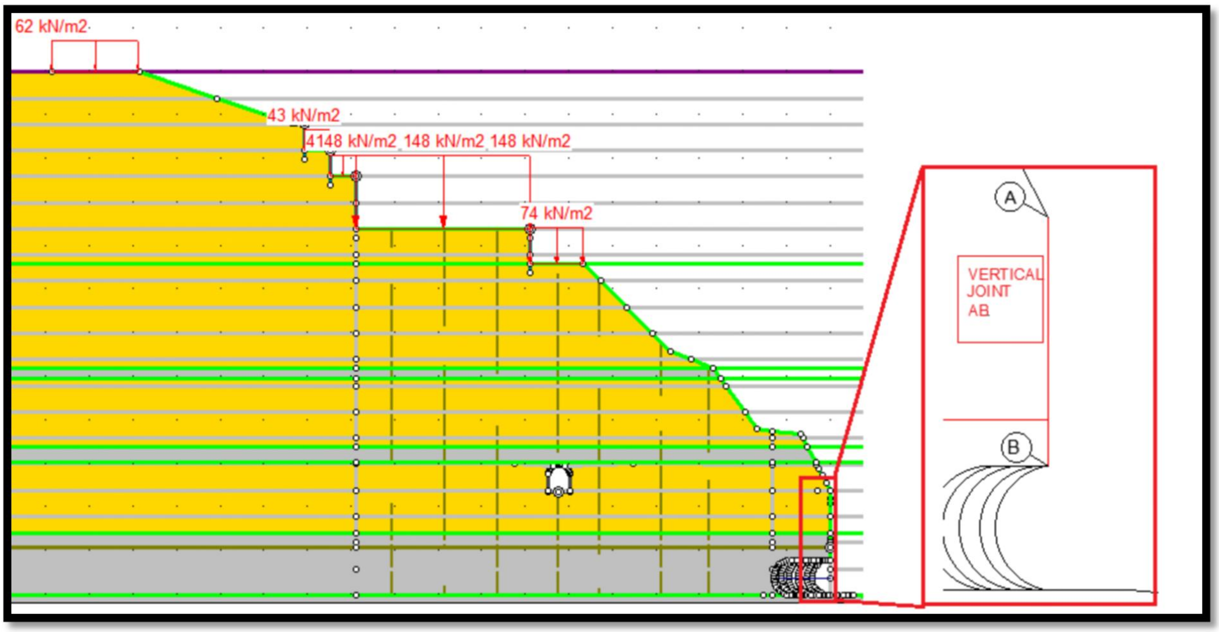

Figure 4.2.1.1 Baseline Model for Forecasting analysis

Table 6 Final Material Properties determined through Back Analysis.

MATERIAL PROPERTIES				
S .No	ARENACEOUS		CALCAREOUS-MARLY	
01	Unit Weight	26.5 kN/m3	Unit Weight	22 kN/m3
02	Poisson's Ratio	0.4	Poisson's Ratio	0.4
03	Young Modulus	5x106 kPa	Young Modulus	5x106 kPa

PEAK STRENGTH				
04	Cohesion	2400 kPa	Cohesion	1300 kPa
05	Tensile Strength	1000 kPa	Tensile Strength	500 kPa
06	Friction Angle	37°	Friction Angle	35°
RESIDUAL STRENGTH				
07	Cohesion	1200 kPa	Cohesion	800 kPa
08	Tensile Strength	500 kPa	Tensile Strength	200 kPa
09	Friction Angle	35°	Friction Angle	33°

The first step involved selecting the baseline model, which was the numerical representation of the cliff validated through back analysis. This model accurately captured the landslide event of March 2024, making it a suitable starting point for predicting future failures. Since coastal erosion is a dominant factor in cliff instability, the second step focused on simulating progressive erosion at the cliff base. By systematically increasing the notch depth in RS2, the model reflected the gradual loss of material due to wave action and weathering, allowing an assessment of its impact on slope stability.

4.2.2 Models with Horizontal Joint

The analysis of the slope with a horizontal joint was conducted to evaluate the impact of this discontinuity on stability under three notch depths: 6.5 m, 10 m, and 14 m. The horizontal joint, included based on observed images, acts as a plane of weakness, significantly influencing the slope's failure mechanisms. Let's recall that the SRF function of RS2 provides the partial results for each step in which the strength parameters of the rock mass are reduced (or increased), step SRF=1 is related to the actual condition of the slope (the parameters are not reduced or increased, they are the original ones) and step Actual SRF refers the condition in which the parameters have been reduced or increased by SRF itself. So, the results were analyzed in terms of yielded elements, maximum shear plastic strain, and total displacement under two conditions: the actual (SRF=1) and the limit one (actual SRF). The last condition is analyzed because, in the case in which SRF>1, the step related to the reduction of the parameters by actual SRF provides information on the possible failure mechanism which could occur if the strength properties of the material would reduce of that quantity, due to some causes like the environmental effect (marine environment in this case).

- **Maximum Plastic Shear Strains**

At SRF = 1, the maximum plastic shear strain distribution varied significantly across the three notch depths (Figure 4.2.2.1). For the 6.5 m notch, the impact was negligible, with no significant concentrations of shear strain observed in limit equilibrium conditions (Figure 4.2.2.1), a maximum plastic shear strain. For the 6.5 m notch, with a Critical SRF of 4.37, 0.0043 was observed above the notch, following the first vertical joint. This indicates localized stress buildup but does not yet suggest widespread failure due to the high stability of the slope. For the 10 m notch, with a Critical SRF of 0.58, a small concentration of 0.003 was identified at the mid-section of the second vertical joint, while a higher concentration of 0.0043 was found between the notch face and the horizontal joint. These concentrations reflect increased stress redistribution and as the SRF is lower than 1, somewhere there is instability. Check if it occurs in correspondence of the slab above the notch, as I expect. In the 14 m notch, with a Critical SRF of 0.43, a higher concentration of 0.0043 was observed on the upper part of the first vertical joint and in the middle upper part of the second, third and fourth vertical joints, as well as between the notch top face and the horizontal joint. These results demonstrate that as the notch depth increases, the horizontal joint amplifies shear strain concentrations, leading to progressive instability.

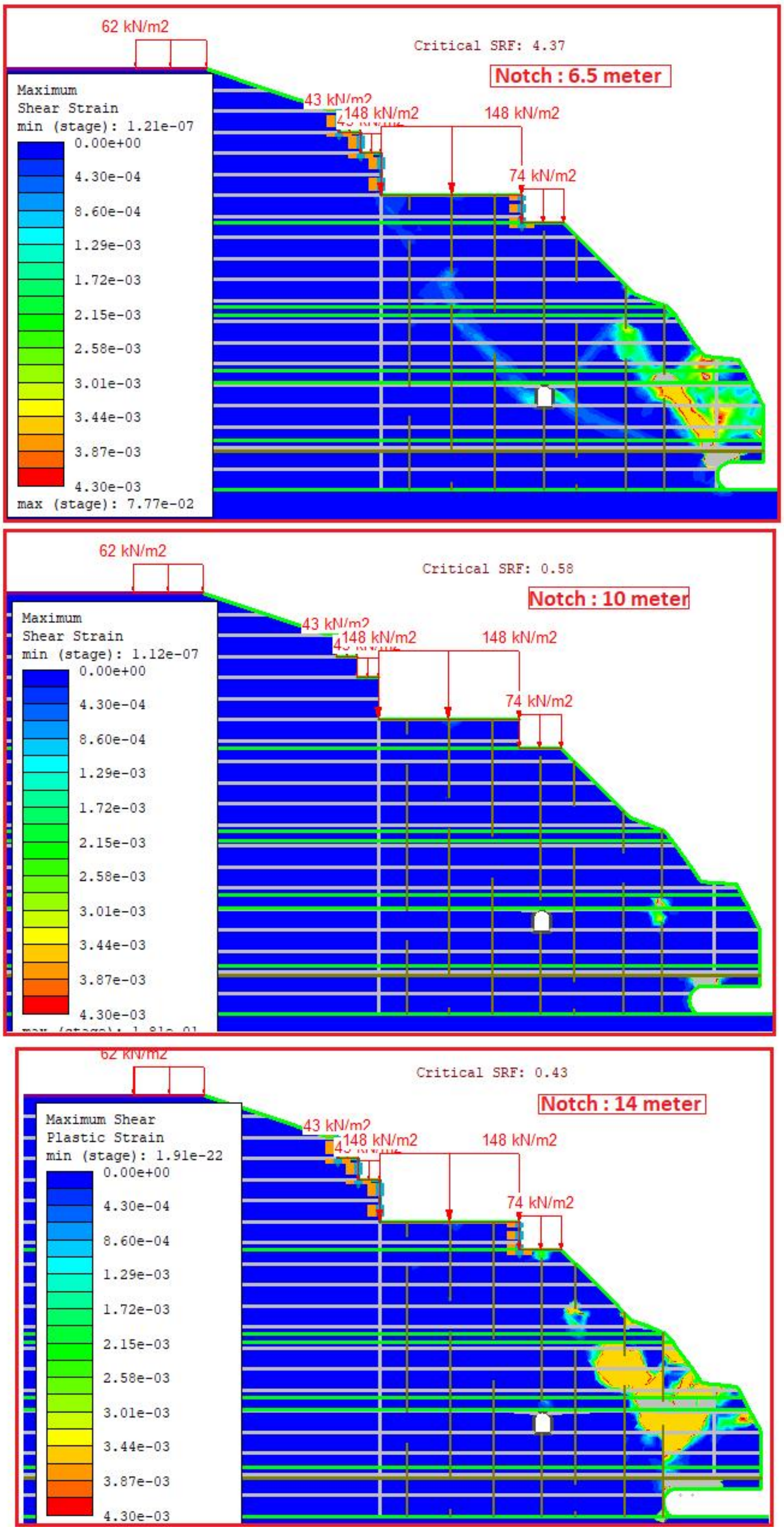

Figure 4.2.2.1 At S.R.F = 1 , Maximum Plastic Shear Strain

In the 10 m notch, two small concentrations of shear strain were identified: 0.0034 on the first vertical joint and 0.0043 between the horizontal joint and the notch top face. These concentrations indicate localized stress buildup but do not yet suggest widespread failure. In contrast, the 14 m notch exhibited a large, cloudy concentration of 0.0043 almost entirely covering the first vertical joint and the notch top face. This widespread shear strain indicates significant stress redistribution and a high likelihood of failure. This widespread shear strain indicates significant stress redistribution and a high likelihood of failure.

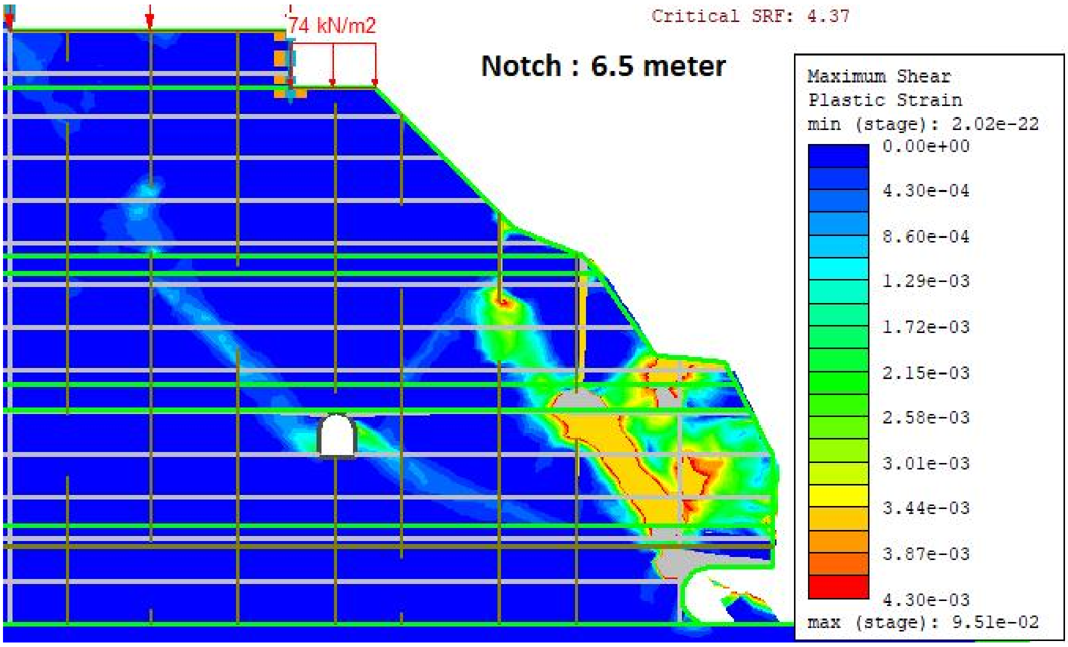

Figure 4.2.2.2 Limit Equilibrium of 6.5 notch depth model in term of Maximum Plastic Shear Strain

- **Yielded Elements**

The distribution of yielded elements varied significantly across the three notch depths. For the 6.5 m notch, a small, cloudy concentration of yielding was observed below the house, indicating localized plastic deformation but no widespread failure. In the 10 m notch, yielding was more pronounced, with concentrations below the house, between the notch top face and the horizontal joint, and at the top part of the second and third vertical joints. These yielded zones reflect increased stress redistribution and the onset of failure mechanisms. For the 14 m notch, yielding was most extensive, with a higher concentration of yielded elements starting from the notch and propagating from the first to the fourth vertical joints. This widespread yielding indicates significant plastic deformation and a high likelihood of failure.

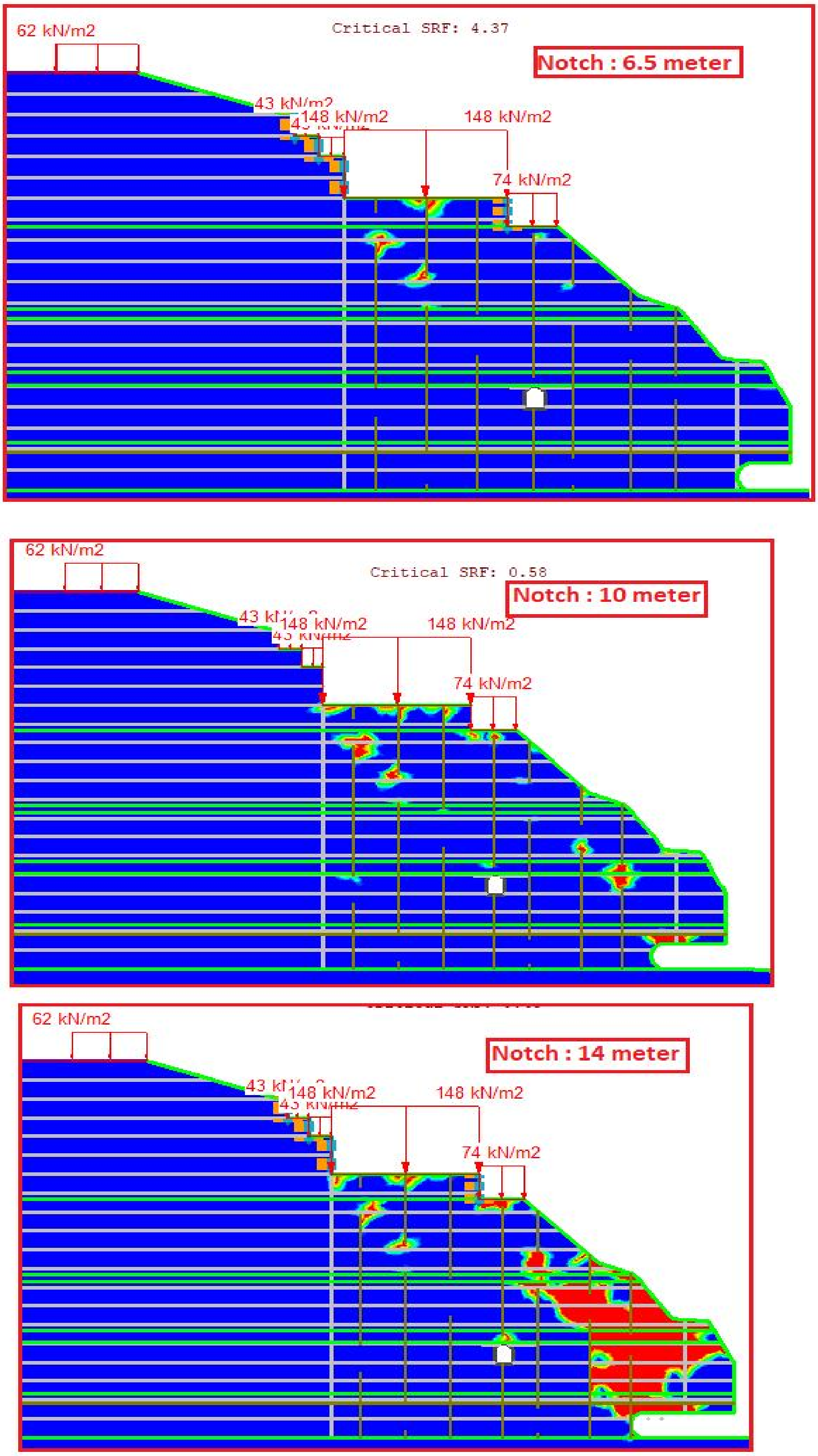

Figure 4.2.2.3 At S.R.F = 1 , Yield Element of 3 different notch model

- **Total Displacement**

In the 10 m notch, concentration was identified 0.5 meter between the horizontal joint and the notch top face. This concentration indicates localized stress buildup but do not yet suggest widespread failure. In contrast, the 14 m notch exhibited a large, cloudy concentration of 0.9 almost entirely covering the first vertical joint and the notch top face. This widespread displacement indicates significant stress redistribution and a high likelihood of failure. This widespread shear strain indicates significant stress redistribution and a high likelihood of failure.

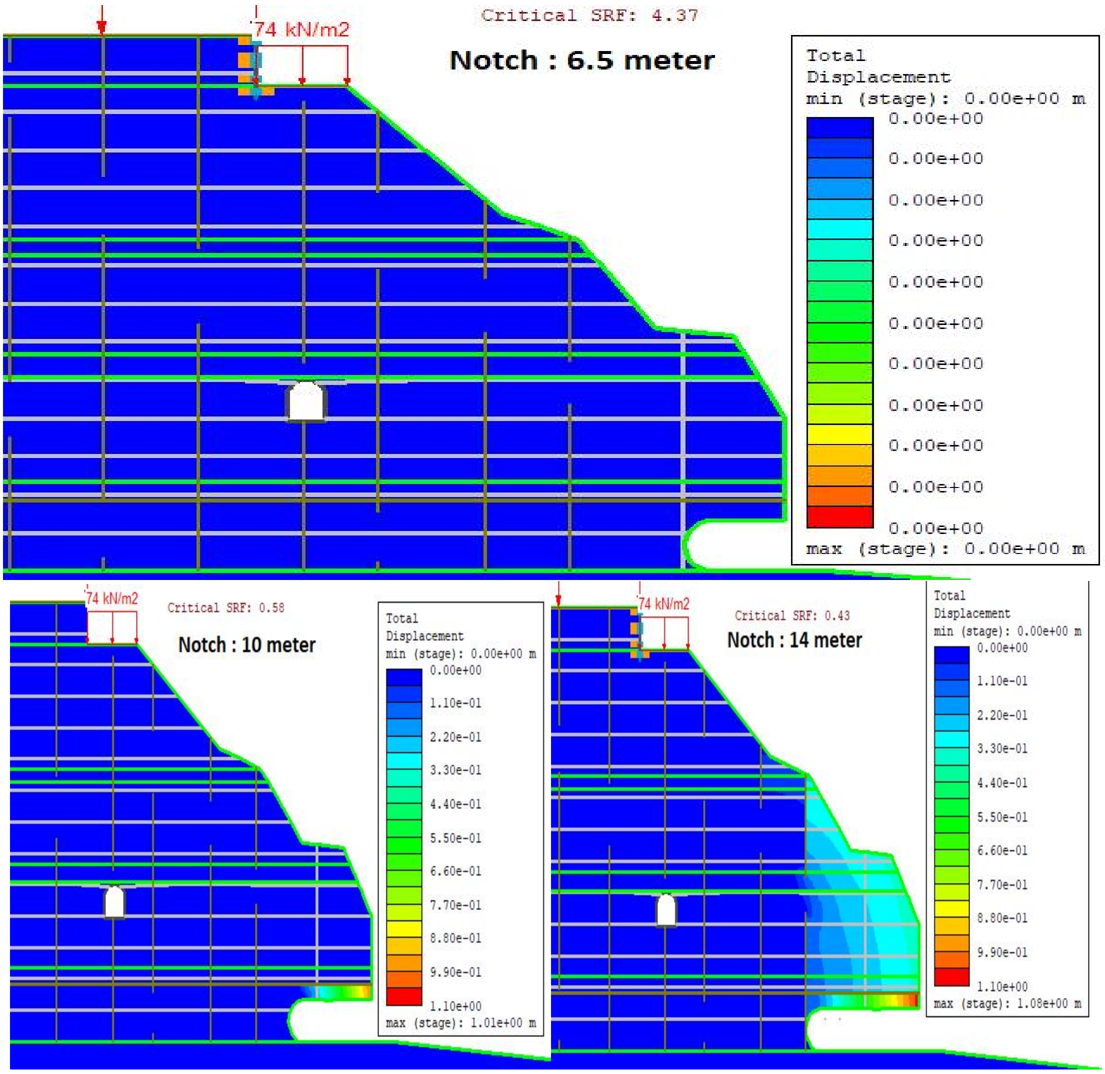

Figure qwr4.2.2.5 At S.R.F = 1 , Total Displacement of 3 different notch model

In limit conditions, the total displacement varied across the three notch depths. For the 6.5 m notch, a displacement of 0.6 meters was observed between the notch top face and the horizontal joint, indicating localized deformation just above the notch. These results demonstrate that while deeper notches lead to more extensive displacement, even the 6.5-meter notch shows localized deformation, highlighting the influence of the horizontal joint on slope behavior.

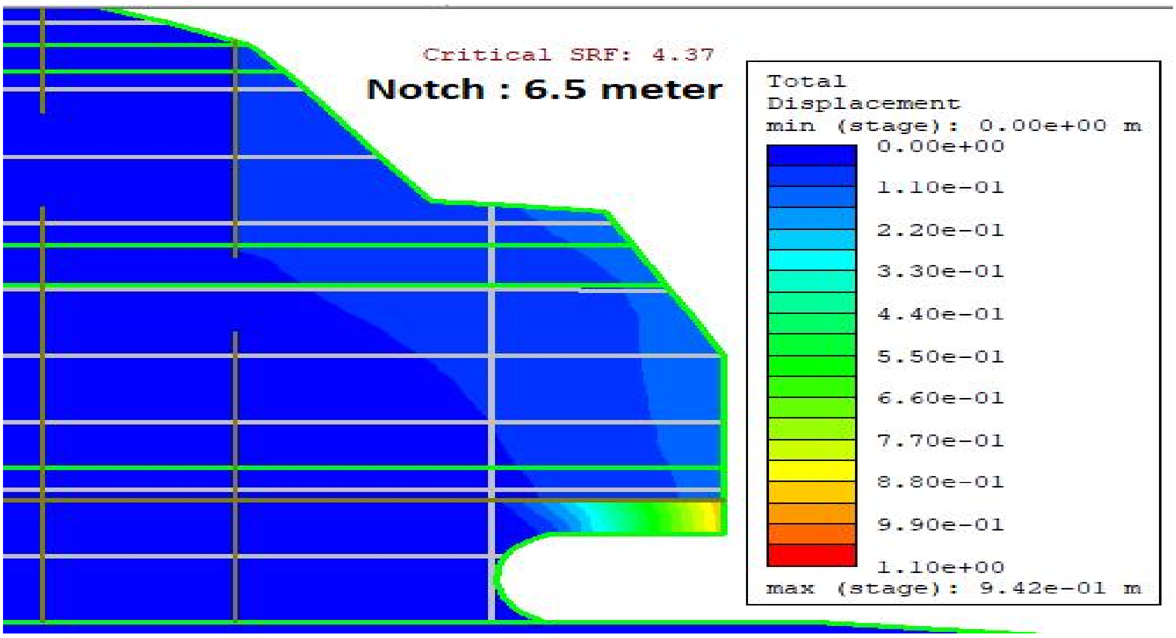

Figure 4.2.2.6 Limit equilibrium condition for 6.5 m depth model in term of Total Displacement

4.2.3 Models without Horizontal Joint

To evaluate the impact of joint persistence uncertainty on slope stability, a second set of models was analyzed without the horizontal joint. These models were created for the same three notch depths 6.5 m, 10 m, and 14 m using identical geometry and material properties, but excluding the horizontal joint. Also in this case, the results were compared in terms of maximum plastic shear strain, yielded elements, and total displacement under two conditions: the actual (SRF=1) and the limit one (actual SRF). This approach provides insights into how the absence of the horizontal joint affects slope stability and deformation under varying notch depths.

- **Maximum Plastic Shear Strains**

At SRF = 1, the maximum plastic shear strain distribution for the models without the horizontal joint varied across the three notch depths. For both the 6.5 m and 10 m notches, the impact was negligible, with no significant concentrations of shear strain observed. This indicates that, in the absence of the horizontal joint, these notch depths do not induce significant stress concentrations or deformation at the point of limit equilibrium. However, for the 14 m notch, a large, cloudy concentration of shear strain was observed, covering almost the entire third vertical joint and the notch top face. This widespread shear strain indicates significant stress redistribution and a high likelihood of failure, even without the horizontal joint.

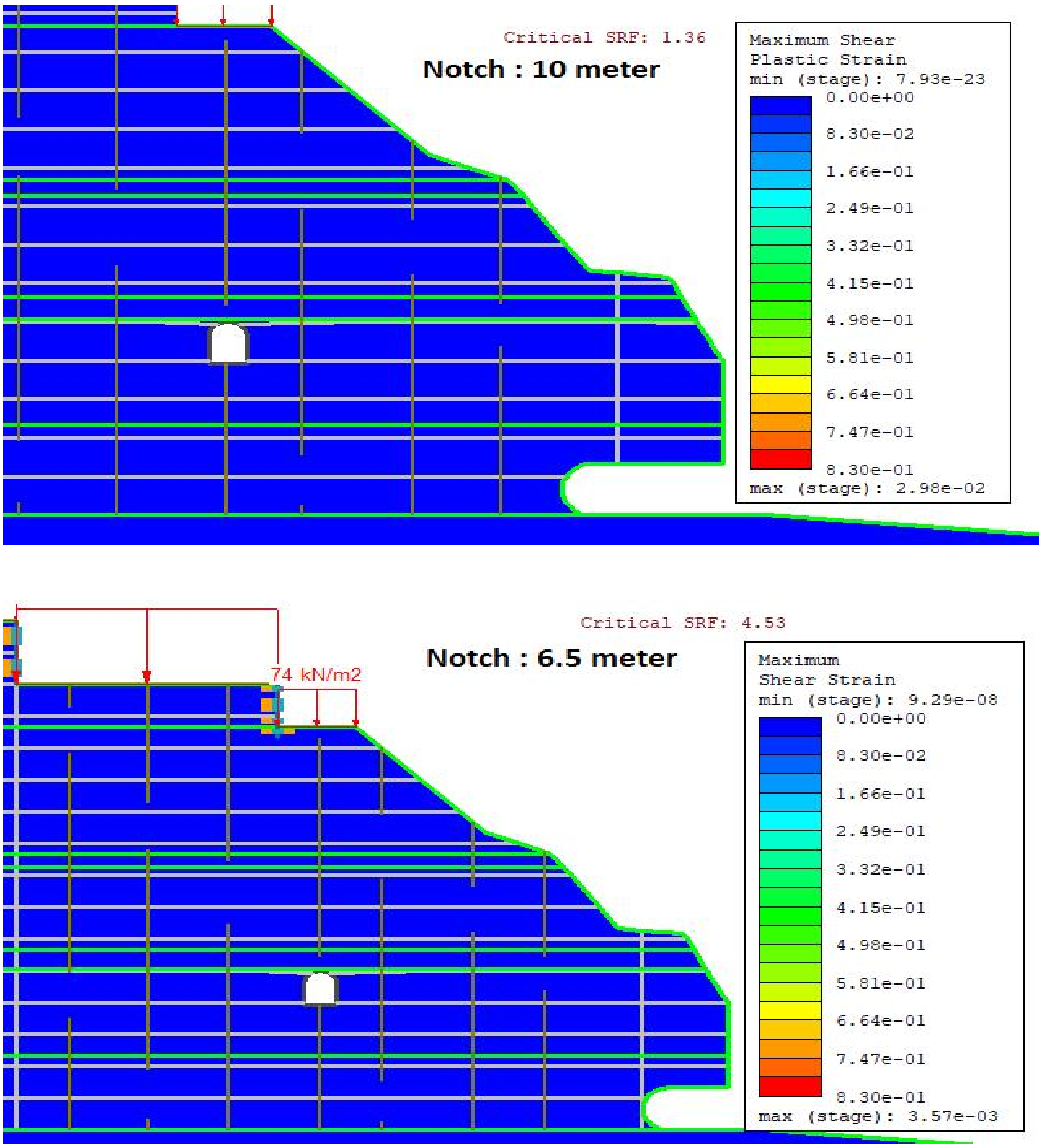

Figure 4.2.3.1 At S.R.F = 1 , Maximum Plastic Shear Strain of 10 and 6.5 meter notch model

At limit equilibrium conditions, the maximum plastic shear strain distribution for the models without the horizontal joint varied across the three notch depths. For the 6.5 m notch, with a Critical SRF of 4.53, the impact was negligible, indicating minimal stress concentrations. In the 10 m notch, with a Critical SRF of 1.36, impactful concentrations of shear strain were observed at the mid-sections of the second and third vertical joints, reflecting increased stress redistribution and marginal stability.

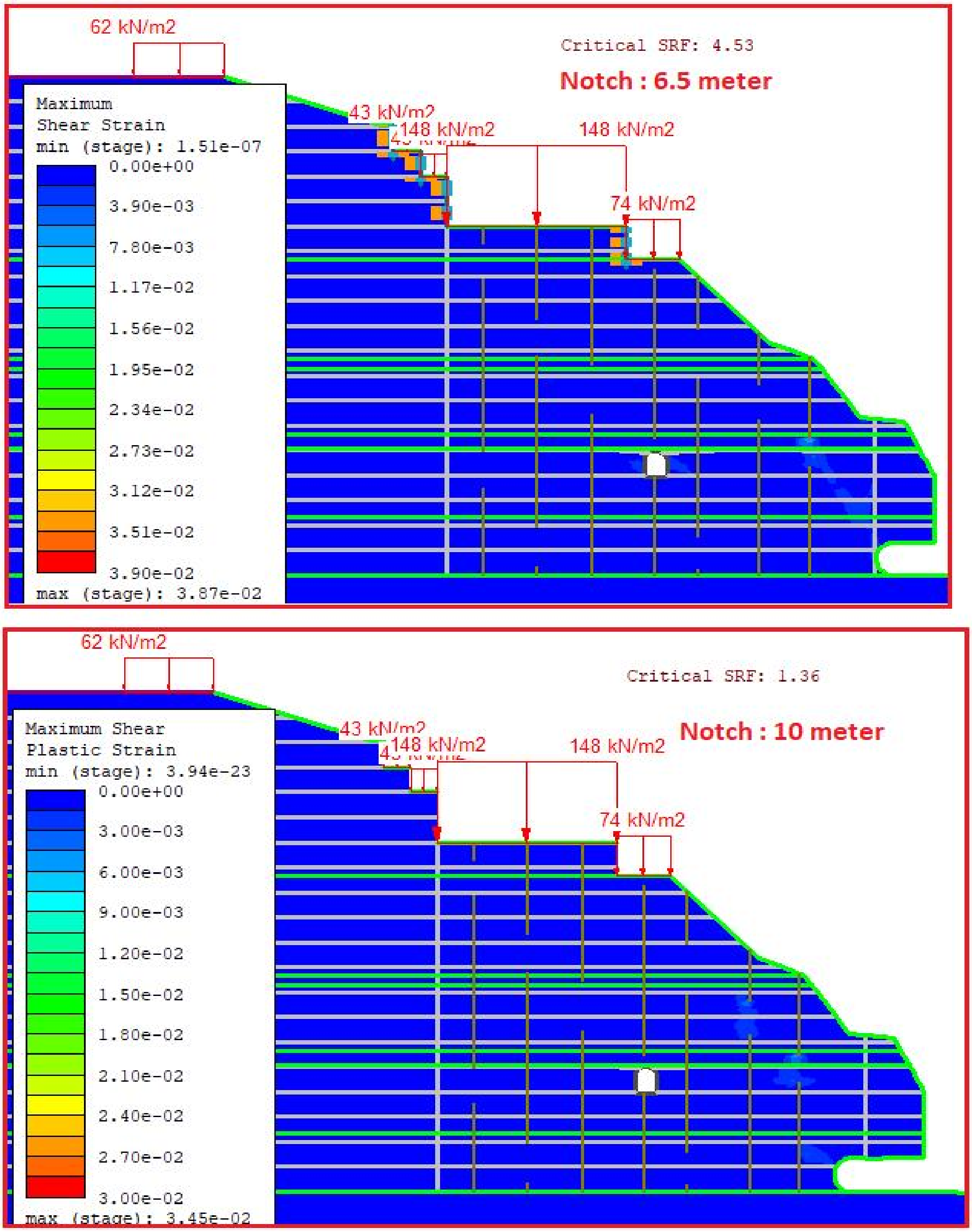

Figure 4.2.3.2 Limit equilibrium condition for 6.5 and 10 m notch depths model in term of Maximum Plastic Shear Strain

- **Yielded Elements**

At SRF = 1, the distribution of yielded elements for the models without the horizontal joint varied across the three notch depths. For the 6.5 m notch, a small, cloudy concentration of yielding was observed below the house, indicating localized plastic deformation but no widespread failure. In the 10 m notch, with a Critical SRF of 1.36, yielding was concentrated above the notch and along the first and second vertical joints, which could potentially cause whole block failure. For the 14 m notch, with a Critical SRF of 0.49, yielding was most severe, starting on the first and second vertical joints,
indicating significant instability and a high risk of catastrophic failure.

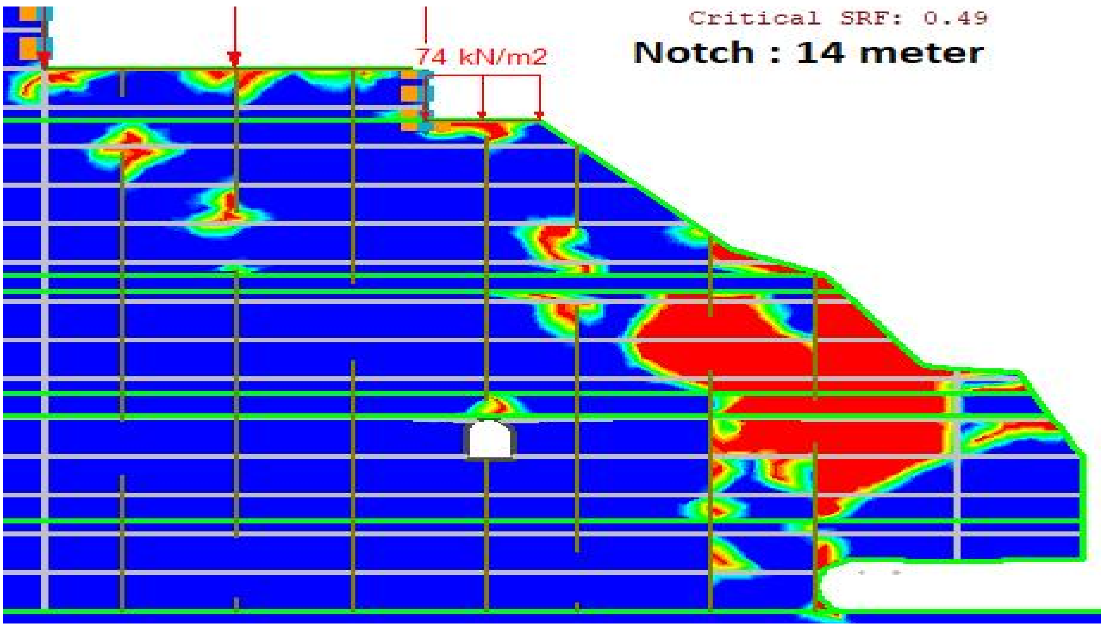

Figure 4.2.3.3 At S.R.F = 1 , Yielded Element of 14 meter notch model

- **Total Displacement**

At SRF = 1, the total displacement for the models without the horizontal joint varied across the three notch depths. For both the 6.5 m and 10 m notches, there was no measurable movement (not a single digit displacement), indicating that the slope remains stable and has not yet undergone significant deformation at the point of limit equilibrium. However, for the 14 m notch, a significant displacement of 0.525 meters was observed, starting from the notch end and extending to the first vertical joint. This displacement pattern suggests the potential for whole block failure, highlighting the increased risk associated with deeper notch depths.

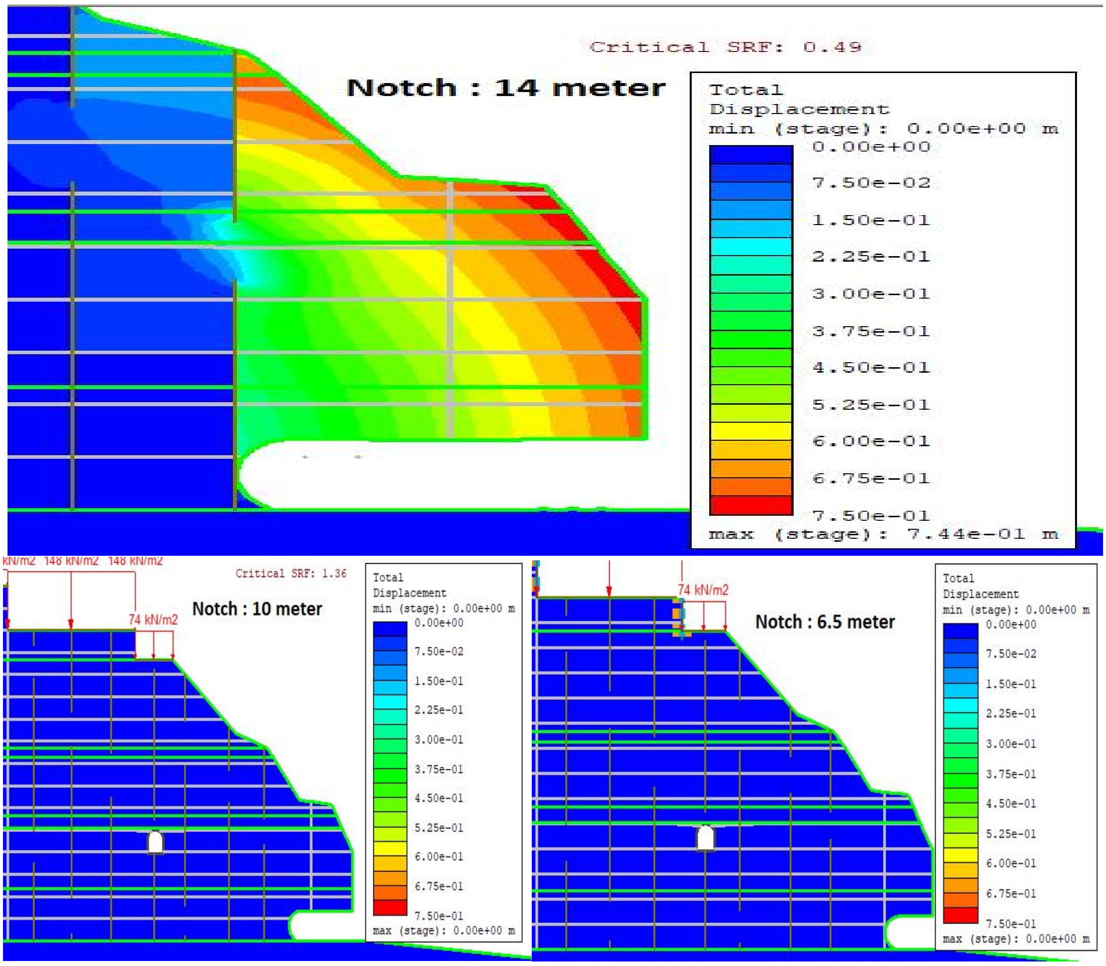

Figure 4.2.3.4 At S.R.F = 1 , Total Displacement of 3 different notch model

At equilibrium conditions, the 6.5 m notch showed, displacements of 0.02 meters from the notch to the house, and 0.0584 meters were noted above the notch to the first vertical joint, indicating localized deformation. In the 10 m notch, the impact was negligible, with no significant displacement observed, reflecting stable conditions.

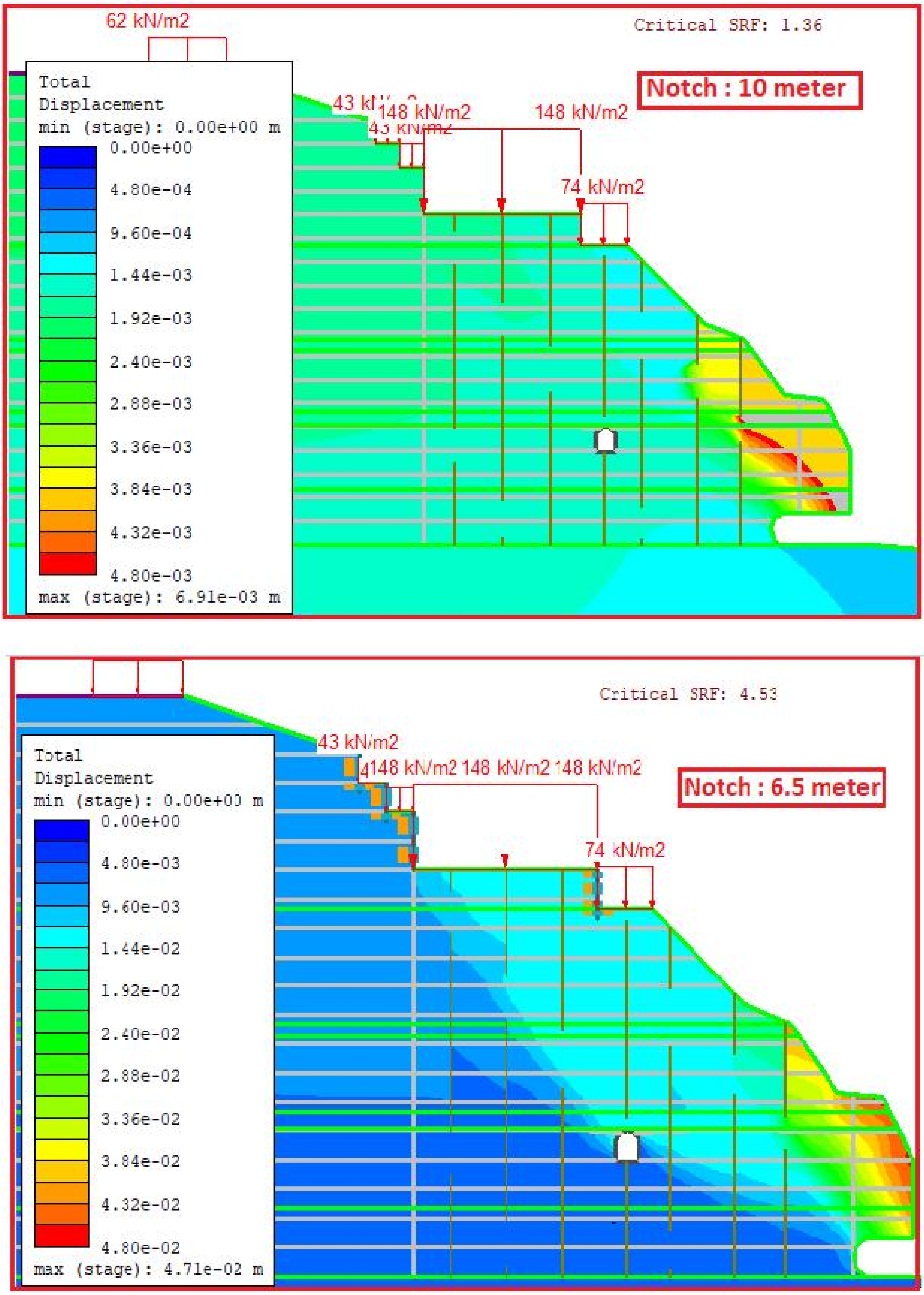

Figure 4.2.3.5 Vary S.R.F of 6.5 and 10 meter notch depth model in term of Total Displacement

5 Conclusion

The study reported in this thesis is devoted to analyses the stability problem of a cliff in a touristic area, on the top of which some buildings have been constructed. The analysis has been performed by the numerical approach of Finite Elements Method and the model used has been reconstructed with the maximum detail, according to the information available. The structure of the rock mass constituting the cliff was not well known so, some assumptions have been reasonably done. The model has been validated by a back analyses, on the basis of a past instability event. Then, a forecasting study has been carried out, to investigate the effect of the progressive advancement of the notch due to the erosive effect of the sea waves. The analysis of slope stability with a horizontal joint for three notch depths 6.5 m, 10 m, and 14 m revealed significant variations in stability, deformation, and failure mechanisms. For the 6.5 m notch, the slope remained stable with minimal yielding and displacement, though localized deformation was observed near the joints. The 10 m notch exhibited marginal stability, with increased yielding and displacement concentrated along the joints and notch face. The 14 m notch showed severe instability, with widespread yielding, high shear strain, and significant displacement, indicating a high risk of block failure. These results highlight the critical role of the horizontal joint in amplifying stress concentrations and deformation, particularly for deeper notches. However, in no cases the stability of buildings is put at risk, in fact the presence of joints in the rock mass provides a localization of the instability close to toe of the cliff.

Table 7 Critical SRF Values with Horizontal Joint

Notch Depth	Critical SRF	Stability Condition	Key Observation
6.5 m	4.37	Stable	Localized yielding and displacement; minimal impact on overall stability.
10 m	0.58	Marginally Stable	Increased yielding and displacement; stress concentrations along the joints.
14 m	0.43	Unstable	Widespread yielding, high shear strain, and significant displacement; high risk of block failure.

The analysis of slope stability without the horizontal joint for three notch depths 6.5 m, 10 m, and 14 m revealed distinct trends in stability and deformation. For the 6.5 m notch, the slope remained stable with negligible yielding and displacement, though localized deformation was observed near the notch. The 10 m notch exhibited marginal stability, with increased yielding and displacement concentrated above the notch and along vertical joints, indicating the potential for block failure. The 14 m notch showed severe instability, with widespread yielding, high shear strain, and significant displacement, confirming a high risk of catastrophic failure. These results demonstrate that while the absence of the horizontal joint improves stability for smaller notch depths, deeper notches still pose significant risks.

Table 8 Critical SRF Values without Horizontal Joint

Notch Depth	Critical SRF	Stability Condition	Key Observation
6.5 m	4.53	Stable	Negligible yielding and displacement; minimal impact on overall stability.
10 m	1.36	Marginally Stable	Increased yielding and displacement; potential for block failure.
14 m	0.49	Unstable	Widespread yielding, high shear strain, and significant displacement; high risk of catastrophic failure.

The analysis of cliff stability by considering the erosive process in the notch at the toe of the cliff, with and without the horizontal joint, reveals distinct failure mechanisms. Without the horizontal joint, the primary failure originates from the notch depth and propagates to the first vertical joint, potentially causing the entire block to fail (Figure 4.2.3.1 - a). In contrast, with the horizontal joint, failure typically initiates between the notch upper part and the horizontal joint before extending to the first vertical joint, leading to local block failure (Figure 4.2.3.1 - b). Additionally, if some environmental actions induce the reduction of the strength properties of the rock mass, a secondary long-term failure mechanism was identified, which could impact the house also when the notch depth is 6.5 m long (Figure 4.2.3.1 - c). However, the time needed to induce a so big reduction of the strength parameters (about 4 times lower than the natural ones) is reasonably lower than the lifetime of the houses, minimizing immediate risks. These findings highlight the critical role of the structural conditions of the rock mass in influencing failure mechanisms and emphasize the importance of monitoring and reinforcing the area close to the notch (by installing some stabilizing elements like bolts, for example) and protecting the cliff face exposed to the sea against the weathering induced by the aggressive marine environment (for example, by means of geo-membranes).

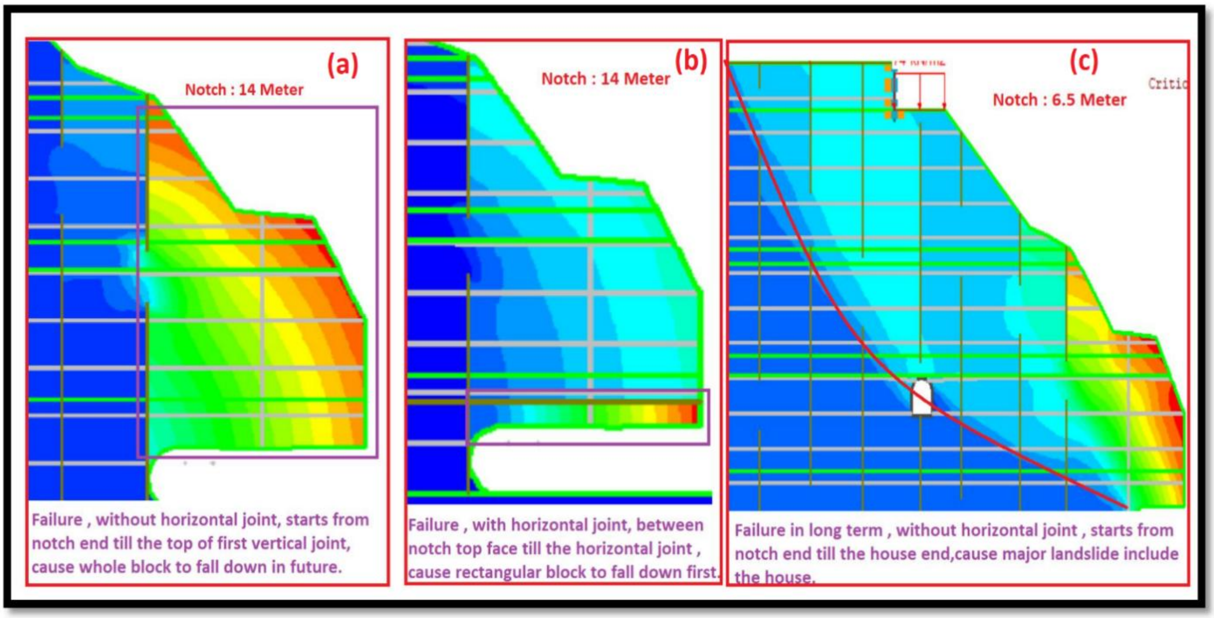

Figure 4.2.3.1 Predicted Failures

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