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Geomorphological Coastal Slope Instability and Susceptibility Mapping in Safi, Morocco

Instabilidade geomorfológica em vertentes costeiras e cartografia de susceptibilidade em Safi, Marrocos

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ABSTRACT

Rocky cliff coasts constitute approximately half of the world's coastline and support human activities and diverse ecosystems but are prone to landslides, a key geomorphological process. This study assesses mass movement susceptibility along Safi's coast in Morocco by analyzing 297 mass movements using topographic, geological, and hydrological predisposing factors according to the information value model. The susceptibility model revealed that 40.62% of Safi's rocky coast is highly susceptible to slope instability.

Key-words: *Rocky coasts, Coastal slope instability, Landslide susceptibility, IV model, Geomorphological processes, Safi, Morocco*

1. INTRODUCTION

Coastal areas, serving as vital transition zones between land and sea, are shaped by complex processes and sustain diverse ecosystems. However, intensified human activity along coastlines has led to unsustainable land use practices and conflicts exacerbated by natural dynamics like sea level rise and coastal erosion (El Bchari et al., 2019; Mbark, 2021; Ougougdal et al., 2020). Rocky cliff coastlines, constituting over half of the world's coastlines, are particularly prone to erosion and landslides due to factors like wave action, tides, cliff morphology, and geology and rainfall (Sunamura, 1992; Young & Carilli, 2019).

This research aims to evaluate mass movement susceptibility in Safi's coastal cliff systems and identify the key predisposing factors influencing the spatial distribution of various mass movement types. The main objectives include: (i) categorizing the type and location of each mass movement, (ii) pinpointing the most significant conditioning factors governing the spatial distribution of different mass movement types, (iii) assessing and weighting the various conditioning factors using the Information Value (IV) method, (iv) determining mass movement susceptibility in Safi's coastal cliffs for different mass movement types and categorizing susceptible areas based on mass movement occurrence, and (v) validating the susceptibility map through Receiver Operating Characteristic (ROC) - Curve Area Under the Curve (AUC) analysis.

2. STUDY AREA AND METHODOLOGY

The coastal area of Safi (Fig. 1-A), extending approximately 30 km from Cap Cantin to the Safi harbor, in Morocco, displays diverse cliff morphologies influenced by lithological composition and rock resistance (Minoubi, 1998; Witam, 1988). These cliffs, ranging from 9 m to 145 m in height, feature varied cross-profile slopes and distinct geological layers, including Upper Jurassic limestones, lower Cretaceous bioclastic limestone, and Plio-Quaternary sandstones (Elfakih et al., 2020). The region's hydrogeology, characterized by two aquifer systems, contributes to coastal processes, with springs along the cliffs influencing mass movement dynamics. Fractures and fault zones in sandstone and limestone beds play a crucial role in cliff instability, with predominant fracture directions impacting collapse susceptibility (Ferré & Ruhard, 1975). Safi's semi-arid climate, experiencing irregular rainfall and winds predominantly from the E and NE, further influences coastal dynamics (Minoubi, 2018). The Safi coastal region is also characterized by diverse geological features and landslides are a prevalent in coastal slope. In the nearby areas, different factors such as elevation, slope, lithology, and drainage play significant roles as predisposing factors in landslide susceptibility (Khouz et al., 2022).
Alongside the natural coastal dynamic processes, Safi's population growth and coastal urbanization pose growing challenges, with increased overcrowding in coastal zones and shifts from agricultural to industrial sectors (Minoubi, 2018).

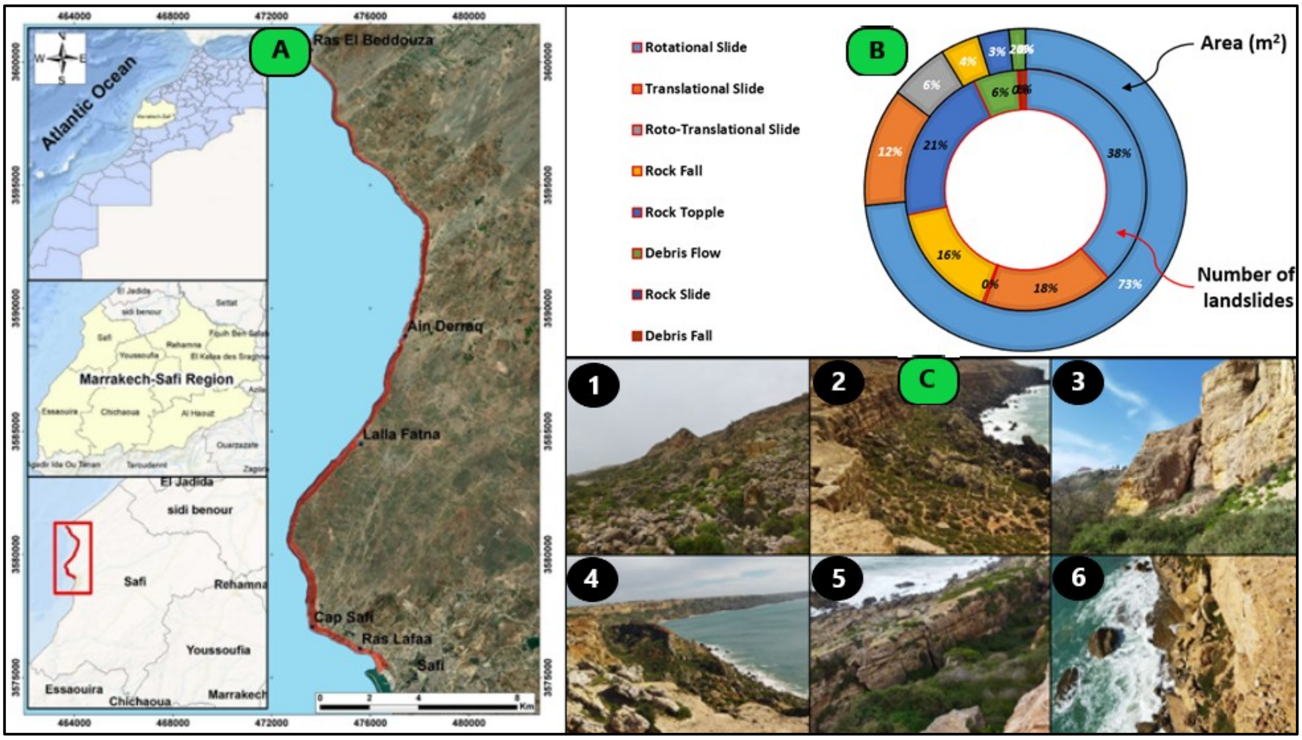

Figure 1-A. Location of the Safi coastal area. B. The relative distribution of mass movements by number and area in Safi coastal area. C. Mass movement type examples in Safi coastal area: 1, 2 and 3: Rotational slide with back tilting. 4 and 5: Translational slide with seaward tilting. 6: Rock falls.

Using diverse data sources, the study analyses coastal mass movement susceptibility, highlighting the significance of field surveys and validation (Marques et al., 2011). The methodology outlines the creation of a mass movement inventory based on field data, orthophotomaps and satellite images interpretation and field validation. Slope instability classification was based on failure surface type, and the compilation of 14 conditioning factors grouped into categories such as topographical, geomorphological, lithological, and hydrogeological (Marques et al., 2011; Gilham, 2018; Khouz et al., 2022; F. Marques, 2018), which are: Aspect, Slope, Curvature profile, Curvature plan, Cliff Height, Topographic Position Indec (TPI), Slope Over Area Ratio (SOAR), Slope deposit protection, Beach protection, Permanent drainage, Spring presence, Cliff Lithology and Cliff Toe lithology. Employing the Information Value method (Yin & Yan, 1988), susceptibility models are developed using pixels and elementary terrain units (ETU), subsequently validated through ROC curves and AUC analysis (Beguería, 2006; Frattini et al., 2010; Rosa et al., 2021; Shano et al., 2020). The establishment of ETUs follows Marques et al. (2011) methodology, defining terrain unit boundaries based on cliff topography and segmenting into 50 m wide sections along the cliff top line. The study results in the evaluation of 681 terrain units of rocky cliffs, assessing stability through the percentage of unstable area in each slope unit.

3. RESULTS AND DISCUSSION

3.1. MASS MOVEMENTS IN THE CLIFFS OF SAFI

The mass movements detected underwent classification based on Cruden and Varnes (1996), identifying 14 distinct types including deep-seated and shallow landslides, rotational and translational slides, and various rock and debris movements. Verification and validation processes, overseen by experts and field workers, led to adjustments in landslide boundaries and the discovery of previously unidentified ones.

The final inventory comprises 297 landslide records, prominently featuring rotational slides (113 occurrences) and rock topples (63 occurrences), with rockslides being the least frequent (one record) (Fig. 1-B). Rotational slides dominate the study area (73%) often accompanied by larger, deeper-seated, and more extensive translational slides. For the ETU, the entire area exhibits some degree of slope instability, reflected in the identification of 681 terrain units, with 86% being fully or partially affected by mass movements, and 20,632 unstable pixels (58%). The non-uniform distribution of mass movements is evident, particularly in the central and southern sections characterized by thicker cliff toes and a higher prevalence of rotational and translational slides (Examples in Fig. 1-C).

3.2. COASTAL LANDSLIDE SUSCEPTIBILITY ASSESSMENT

Evaluating the probability of mass movements in rocky cliffs through the IV model encompassed two methodologies for identifying areas prone to mass movements: one based on pixel-level geoinformation distribution and the other involving the analysis of elementary terrain units.

3.2.1 PIXEL TERRAIN UNITS

Mapping of landslide susceptibility was classified into four categories) using IV model scores (very low (score < -1), low (-1 < score < 0), moderate (0 < score < 1), and high susceptibility (score > 1)) for each mass movement conditioning factor, considering 15 types of mass movements.

Key factors influencing mass movement occurrence in Safi coastal area include cliff height, elevation, lithology, and TPI. For instance, deep-seated landslides are influenced by cliff heights and marl-sandy marls lithology, while shallow mass movements are associated with high slopes and gypsum formations. The spatial distribution of susceptibility classes for Model 1, displaying varied susceptibility levels across the Safi coastal area, with higher susceptibility in the southern and central regions due to rotational and translational slides. Approximately 40% of the cliffs are classified as highly susceptible to all mass movement types, highlighting the importance of considering diverse factors in mass movement susceptibility assessments. All other susceptibility models showed high percentages for very low susceptibility, with a maximum of 99.74% for rock slides. The exception is for deep and shallow landslides, where the highest susceptibility was 40.02% and 36.72% of the study area, respectively (Table 1).

3.2.2. ELEMENTARY TERRAIN UNITS (ETU):

The susceptibility assessment categorizes elementary terrain units (ETUs) into stabilized (42%) and unstabilized (58%) categories. Information Value scores are then reclassified into four levels as the pixels approach. Across all types of mass movements, highly susceptible areas are concentrated in the southern units of the Safi coastal region. The results of ETU landslide

susceptibility, focusing on sections near Ain Derraq and Cap Safi in the middle and southern parts of the study area as the most susceptible. These maps exhibit similar susceptibility patterns to those generated using the pixel approach but offer the advantage of defining susceptible areas in situ using the ETU.
The susceptibility assessment divides elementary terrain units (ETUs) into stabilized (42%) and unstabilized (58%) categories. Information Value scores are then reclassified into four levels as the pixels approach. Highly susceptible to mass movement areas are concentrated in the southern units of the Safi coastal region, especially near Ain Derraq and Cap Safi. The ETU mass movement susceptibility maps show similar patterns to the pixel approach but better define susceptible areas in situ.

Table 1. Percentage of mass movement susceptibility classes

Type	Models	Very low susceptibility	Low susceptibility	Moderate susceptibility	High susceptibility
All Landslides	**Model 1**	17.79%	16.73%	24.86%	40.62%
Rotational Slide	**Model 2**	22.85%	17.42%	19.77%	39.96%
Translational Slide	**Model 3**	36.68%	10.50%	16.03%	36.79%
Roto-Translational Slide	**Model 4**	81.89%	4.13%	4.51%	9.46%
Rock Fall	**Model 5**	36.22%	15.28%	20.40%	28.09%
Rock Topple	**Model 6**	72.23%	3.27%	4.00%	20.50%
Debris Flow	**Model 7**	83.95%	5.04%	3.02%	7.99%
Rockslide	**Model 8**	99.74%	0.01%	0.06%	0.20%
Debris Fall	**Model 9**	95.03%	0.14%	0.20%	4.62%
Deep Rotational Slide	**Model 10**	23.29%	16.81%	21.44%	38.46%
Deep Translational Slide	**Model 11**	63.29%	15.79%	15.96%	4.96%
Deep Landslides	**Model 12**	22.75%	15.99%	21.25%	40.02%
Shallow Rotational Slide	**Model 13**	38.50%	11.78%	15.70%	34.02%
Shallow Translational Slide	**Model 14**	37.32%	16.08%	16.70%	29.89%
Shallow Landslides	**Model 15**	32.21%	14.97%	16.10%	36.72%

3.3. COASTAL LANDSLIDE SUSCEPTIBILITY MODELS VALIDATION

The coastal landslide susceptibility models verified through comparison with independent landslide partitions designated as validation subsets. ROC curves and their respective AUC values were calculated for each model, indicating the effectiveness of the pixel and the ETU approaches. Pixel-based models generally showed AUC values exceeding 0.7, with some models categorized as acceptable, excellent, or outstanding based on their AUC scores. In contrast, most ETU-based models had AUC values below 0.7, suggesting lower validation effectiveness due to reduced resolution. However, the ETU approach remains valuable for on-site interventions. Notably, the total landslide model (Model 1) demonstrated improved prediction with an AUC value of 0.706, indicating the sensitivity of the pixel approach in enhancing model performance. Additionally, AUC graphs for rotational slides (Model 4) and translational slides (Model 7) illustrated good predictive ability, emphasizing the effectiveness of models tailored to specific landslide types compared to total landslide models.

Coastal landslide susceptibility models were verified using independent mass movement validation subsets. Receiver Operating Characteristic (ROC) curves and Area Under Curve (AUC) values were calculated for each model to assess effectiveness. Pixel-based models generally had

AUC values over 0.7, with some rated as acceptable, excellent, or outstanding. Most ETU-based models had AUC values below 0.7, indicating lower validation effectiveness due to reduced resolution, though they remain valuable for on-site interventions. The total landslide model (Model 1) showed improved prediction with an AUC of 0.706, highlighting the pixel approach's sensitivity. AUC graphs for rotational (Model 4) and translational slides (Model 7) showed good predictive ability, underscoring the effectiveness of models tailored to specific landslide types.

4. CONCLUSION

A bivariate statistical method was employed to assess landslide susceptibility across the 30 km coastal of Safi, integrating geological and morphological analyses alongside aerial photos, satellite images, and field surveys. This comprehensive approach identified 40% of the area as highly susceptible to various mass movement types, particularly rotational and translational slides, which constituted 85% of the total area affected by mass movements. Conditioning factors such as cliff height, elevation, TPI class, and specific rock formations contributed to increased susceptibility in the central and southern regions. The northern sector, characterized by wider cliff toes, exhibited comparatively lower susceptibility to landslides.

The correlation between mass movement susceptibility and factors derived from digital elevation models, such as cliff height, elevation, and slope angle, was evident in most susceptibility models, reinforcing their significance in mass movement occurrence. Human activities, notably the construction of tourist parks on translational landslides and wastewater discharge onto cliff faces, were identified as potential contributors to landslide occurrences, particularly in clay and marl-rich areas, with implications for nearby structures. Both pixel and ETU models yielded similar results, offering valuable insights for spatial planning and emergency response in the rocky cliffs of Safi, although the ETU approach's consideration of cliff morphometry may lead to less detailed landslide susceptibility classification compared to the pixel approach, despite its usefulness in territorial management. Geotechnical studies focusing on the southern Safi coastal area are recommended to deepen understanding of landslide-prone zones.

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