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Scenario analysis of debris flows threatening the UNESCO archaeological site of Villa Romana del Casale (Sicily)

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Abstract **– The Italian territory is particularly exposed to natural phenomena such as landslides, floods, earthquakes, volcanic eruptions, subsidence and coastal erosion which every year cause several dozen victims and considerable damage to cultural and environmental heritage sites. In this work, an assessment of the debris flow hazard for the UNESCO site of Villa Romana del Casale (Italy) was carried out, through geomorphological, hydrological investigations, and 2D numerical hydraulic modeling. The analysis has been carried out both at a large scale, by including the entire catchment area, and at site-scale, focusing on local impacts on the monumental remaining. The scenario analysis highlighted the different dynamics of the debris flows, through spatial-temporal maps of deposition areas, water depths and velocity values. The methodology provides useful insights on the most vulnerable archaeological elements inside of the study site and possible protection measures.**

I. INTRODUCTION

The problem of assessing the vulnerability of cultural heritage and historical sites to flood events has been highlighted in several studies both nationally and internationally (Lollino & Audisio, 2006, Lazzari et al. 2006). However, the hydraulic risks associated with floods and landslides are still considered a minor problem in the context of cultural heritage management strategies and activities.

Due to some characteristics that is common to many archaeological sites, they are among the most exposed ones to floods (D'Agostino et al., 2021) or debris flows (Musumeci et al. 2021). The archaeological areas, in fact, are generally part of an excavation, with elevations even of several meters below the natural level of the ground. Debris material and surface runoff waters can accumulate and remain even for long periods within the archeological excavation.

Here, an investigation methodology for the assessment of the debris flow hazard for the Villa Romana del Casale in Piazza Armerina (EN), a UNESCO heritage site since 1997, among the 10 most visited archaeological sites in Italy, is presented. The building of the Villa (III - IV century AD) has two aqueducts, baths, latrines and has 48 rooms for a total of about 4000 square meters. Its very high artistic and historical value is mainly due to the 3500 square meters of polychrome mosaic flooring found almost intact. However, the archaeological site of Villa Romana del Casale is located at the mouth of a small catchment area of 0.75 km^2, with a main reach about 2 km long, which flows into the Nocciara creek, just downstream of the archaeological site. The Nocciara creek is in turn a tributary of the Gela River. The construction of the Villa on three levels, together with the possibility of intercepting the surface runoff waters coming from the upstream catchment area, allowed the collection of rainwater, which was distributed by gravity in the various rooms of the building through a complex system of reservoirs, channels and pipelines. However, due to its position, the Villa has been affected over the centuries by alluvial phenomena and debris flows (Agosta & Alfano, 2007). When, in 1956, it was unearthed, it was buried under a blanket of alluvial detrital material between 3 and 8 meters deep (Barresi, 2005) and still today it is considerably threatened by alluvial and detrital phenomena that periodically damage the unique mosaic decorative apparatus.

In the present work, the generation and propagation of different debris flow scenario events are modeled and a monitoring system of hydraulic and geotechnical quantities is developed. In particular, the main factors responsible for hydro-geomorphological instabilities, generation of landslides and debris flows, rainfall regime, geological and morphological characteristics of the basin and the use of the soil are analyzed.

II. METHODOLOGY

To assess the danger from debris flow for the archaeological site analyzed, geognostic analyzes, measurements, on-site surveys and the creation of models for the simulation of the phenomenon involved were carried out. The analyzes were developed on the scale of the hydrographic basin upstream of the Villa, placed the closing section of the same in correspondence with the archaeological site. Through the study of historical cartography, historical satellite images and field surveys, some unstable areas have been identified along the slopes upstream of the Villa, from which debris flow phenomena could be triggered following intense meteoric events (Figure 1a). The study on the initiation and propagation of possible debris flow events that can impact on the archaeological area was conducted through a multi-scenario analysis that investigates different trigger combinations and different mobilizable volumes within the catchment area. To this aim, two numerical models have been developed for the numerical simulation of event scenarios. The modeling activities supported the development of a sensor network, designed to evaluate potential risks. Numerical simulations were carried out using the FLO-2D computational code, a two-dimensional model that adopts a single-phase rheological approach, implemented through empirical relationships developed by O'Brien & Julien (1985).

The elevation data implemented within the calculation grids of the models are obtained by interpolating the elevation data of a 2x2m DTM. The temporal evolution of the simulated event is represented by a triangular solid-liquid hydrograph, whose duration is fixed in 6 min, representative of a high specific intensity event.

The two different numerical models created are:

- the first model ("closed" model), characterized by a square mesh calculation grid, with cells of 5 meters side, is aimed at large-scale investigations of the dynamics of the propagation from the trigger areas along the slopes of the basin, up to the archaeological site (Figure 1b). The building of the Villa is modeled as a closed body, which cannot be overtopped, and it is unable to incorporate debris volumes. Using this model, 9 different event scenarios were simulated, each of which characterized by a different thickness of mobilized detrital layer in the upstream region, between 20 cm and 1 m, and 15 different combinations of triggering of unstable areas, for a total of 135 simulations (Table 1).
- the second model ("open" model), whose representation of the Villa is more detailed, is characterized by a square grid with a side equal to 2 meters. The Villa is modeled considering the different access routes to the building, through the doors and windows of the Villa. o creates the model, a three-dimensional reconstruction of the archaeological area and the historic building of the Villa del Casale was carried out through an analysis of the plans, sections and together with the digital model of the terrain. Every single room has been reconstructed with attention to the footfall level, the slopes of the land and the sizing of the openings (Figure 1c). Three different event scenarios were simulated this model, considering three different thickness of debris layer mobilized by the four triggering areas.

III. RESULTS

The numerical simulations carried out make it possible to define, for each simulated scenario, the arrival time at the archaeological area of the various casting events, the storage volumes and the effectiveness of the existing hydraulic defense works. This event scenario-based approach has been used by several authors (Dietrich et al., 2003; Bellugi et al. 2015) to overcome the difficult problem of determining the return period of a debris flow event.

For both the numerical models implemented, control cells were identified both outside the historical factory and inside the Villa in the case of the second model. For each of the cells, the trend over time of the maximum flow depth, the final deposition height and the maximum velocity of the debris flow were analyzed. The results of the first model (closed Villa) show how the archaeological area, located 5-13 m below the surrounding alluvial plain, is flooded by debris mobilized for the different scenarios considered, with maximum depths at some points almost 5m high and final deposit heights greater than 1m (see Figure 2). This is because the incoming debris flow, finding an obstacle represented by the Villa, tends to accumulate upstream and slowly expose itself throughout the archaeological area.

The results reveal that the existing hydraulic defense channel is not sufficient to protect the site from incoming debris, as this only operates during the initial phase of the debris flow event. The arrival times of the simulated events from the trigger areas to the archaeological site were then evaluated, ranging from 40 minutes to 6 hours. Furthermore, it was possible to observe how the presence of a low-sloping area immediately upstream of the Villa and the subsequent low slopes within the archaeological area induce very low propagation velocity over the area (about 0.1-0.5m/s). Small flow velocities reduce the risk that the flow could cause damage to the structure of the Villa, through dynamic impacts, but at the same time large sediment volumes are deposited in the area and must be properly managed.

The common approach, widely used in the study of the propagation of hydraulic phenomena in urban contexts or where there is a built environment, is to ignore the ability of buildings to trap water or debris flow (Stancanelli & Foti, 2015), to the advantage of safety. This approach, followed for the first model created on the archaeological area of Villa del Casale, allows a rough assessment of the danger in relation to multiple event scenarios. However, the approach described for the first model places limits on the knowledge of the propagation dynamics of the debris flow within the premises of the Villa and any residual volumes, essential for the protection of the heritage kept there. These limitations are partially overcome with the realization of the second model created in the present work.

The results relating to the second model created (open villa) show how the incoming debris flow, having the possibility of entering the building, easily arrives on the downstream excavation face, with final deposits even greater than 4 meters, with lowering of the detrital peaks in correspondence with the excavation face upstream of the Villa (Figure 3). The analysis of the control cells inside the Villa made it possible to identify some critical areas for the deposition of debris.

A comparison between the two models is shown in the Figure 4.

ACKNOWLEDGEMENTS

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Table 1 – Matrix of simulated scenarios, in which the different scenarios are considered (thickness from 0.2 to 1 meter) and combinations of triggering of unstable area.

<table>
<tr><td colspan="5">Possible event scenarios [S]</td><td colspan="9">Possible event scenarios [S]</td></tr>
<tr><td colspan="5">0.2m 0.3m 0.4m 0.5m 0.6m 0.7m 0.8m 0.9m 1m</td><td>0.2m</td><td>0.3m</td><td>0.4m</td><td>0.5m</td><td>0.6m</td><td>0.7m</td><td>0.8m</td><td>0.9m</td><td>1m</td></tr>
<tr><td colspan="5">Possible combinations of triggers</td><td colspan="9">Volumes mobilized</td></tr>
<tr><td>C</td><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td colspan="9">m^3</td></tr>
<tr><td>1</td><td>X</td><td>-</td><td>-</td><td>-</td><td>1380</td><td>2070</td><td>2750</td><td>3440</td><td>4130</td><td>4820</td><td>5500</td><td>6190</td><td>6880</td></tr>
<tr><td>2</td><td>X</td><td>X</td><td>-</td><td>-</td><td>3510</td><td>5260</td><td>7000</td><td>8760</td><td>10510</td><td>12260</td><td>14000</td><td>15760</td><td>17510</td></tr>
<tr><td>3</td><td>X</td><td>X</td><td>X</td><td>-</td><td>4140</td><td>6200</td><td>8250</td><td>10330</td><td>12390</td><td>14450</td><td>16500</td><td>18580</td><td>20640</td></tr>
<tr><td>4</td><td>X</td><td>X</td><td>-</td><td>X</td><td>3760</td><td>5640</td><td>7500</td><td>9390</td><td>11260</td><td>13140</td><td>15000</td><td>16890</td><td>18760</td></tr>
<tr><td>5</td><td>X</td><td>-</td><td>X</td><td>-</td><td>2010</td><td>3010</td><td>4000</td><td>5010</td><td>6010</td><td>7010</td><td>8000</td><td>9010</td><td>10010</td></tr>
<tr><td>6</td><td>X</td><td>-</td><td>X</td><td>X</td><td>2260</td><td>3390</td><td>4500</td><td>5640</td><td>6760</td><td>7890</td><td>9000</td><td>10140</td><td>11260</td></tr>
<tr><td>7</td><td>X</td><td>-</td><td>-</td><td>X</td><td>1630</td><td>2450</td><td>3250</td><td>4070</td><td>4880</td><td>5700</td><td>6500</td><td>7320</td><td>8130</td></tr>
<tr><td>8</td><td>-</td><td>X</td><td>-</td><td>-</td><td>2130</td><td>3190</td><td>4250</td><td>5320</td><td>6380</td><td>7440</td><td>8500</td><td>9570</td><td>10630</td></tr>
<tr><td>9</td><td>-</td><td>X</td><td>X</td><td>-</td><td>2760</td><td>4130</td><td>5500</td><td>6890</td><td>8260</td><td>9630</td><td>11000</td><td>12390</td><td>13760</td></tr>
<tr><td>10</td><td>-</td><td>X</td><td>X</td><td>X</td><td>3010</td><td>4510</td><td>6000</td><td>7520</td><td>9010</td><td>10510</td><td>12000</td><td>13520</td><td>15010</td></tr>
<tr><td>11</td><td>-</td><td>X</td><td>-</td><td>X</td><td>2380</td><td>3570</td><td>4750</td><td>5950</td><td>7130</td><td>8320</td><td>9500</td><td>10700</td><td>11880</td></tr>
<tr><td>12</td><td>-</td><td>-</td><td>X</td><td>-</td><td>630</td><td>940</td><td>1250</td><td>1570</td><td>1880</td><td>2190</td><td>2500</td><td>2820</td><td>3130</td></tr>
<tr><td>13</td><td>-</td><td>-</td><td>X</td><td>X</td><td>880</td><td>1320</td><td>1750</td><td>2200</td><td>2630</td><td>3070</td><td>3500</td><td>3950</td><td>4380</td></tr>
<tr><td>14</td><td>-</td><td>-</td><td>-</td><td>X</td><td>250</td><td>380</td><td>500</td><td>630</td><td>750</td><td>880</td><td>1000</td><td>1130</td><td>1250</td></tr>
<tr><td>15</td><td>X</td><td>X</td><td>X</td><td>X</td><td>4390</td><td>6580</td><td>8750</td><td>10960</td><td>13140</td><td>15330</td><td>17500</td><td>19710</td><td>21890</td></tr>
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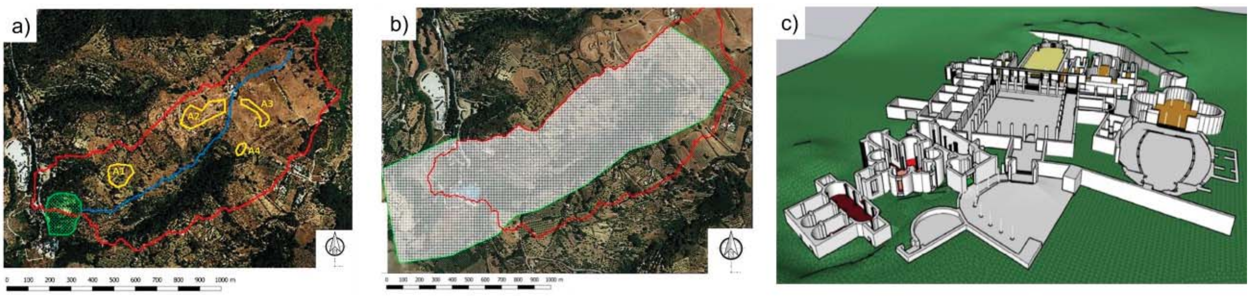

Figure 1: (a) Identification of the 4 unstable area (b) numerical model with 5x5 meters square mesh grid (c) 3D model of the Villa Romana del Casale

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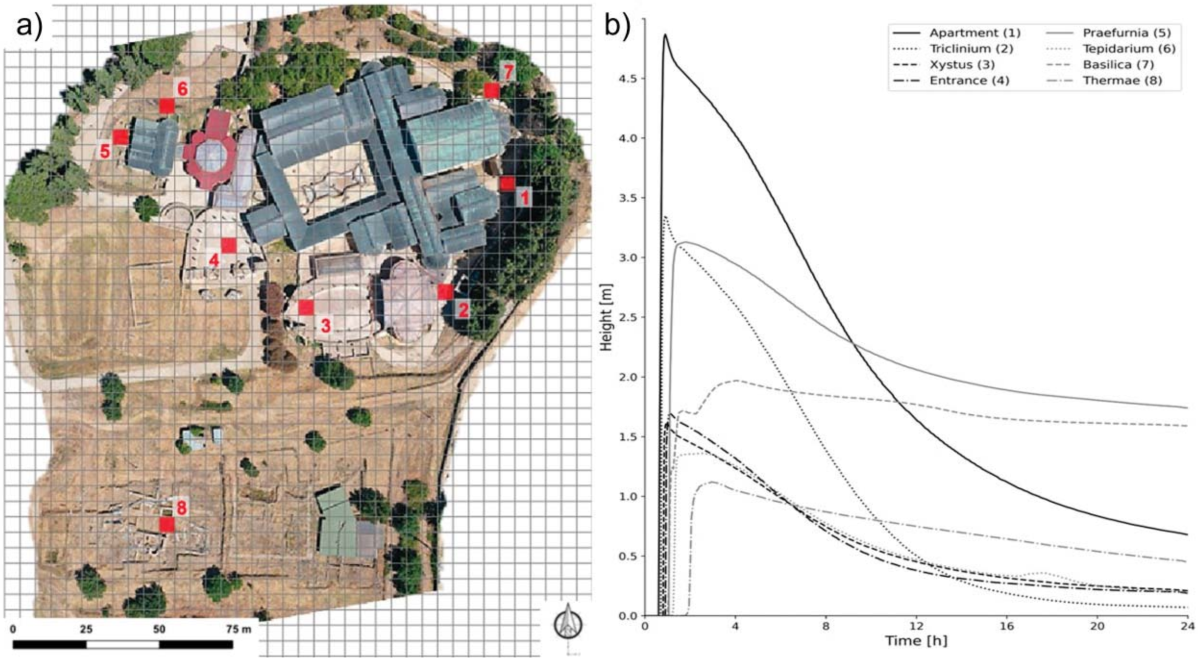

Figure 2: (a) position of the control cells within the archaeological area for "closed Villa" model (b) trend of the heights of the debris flow for one of the simulations.

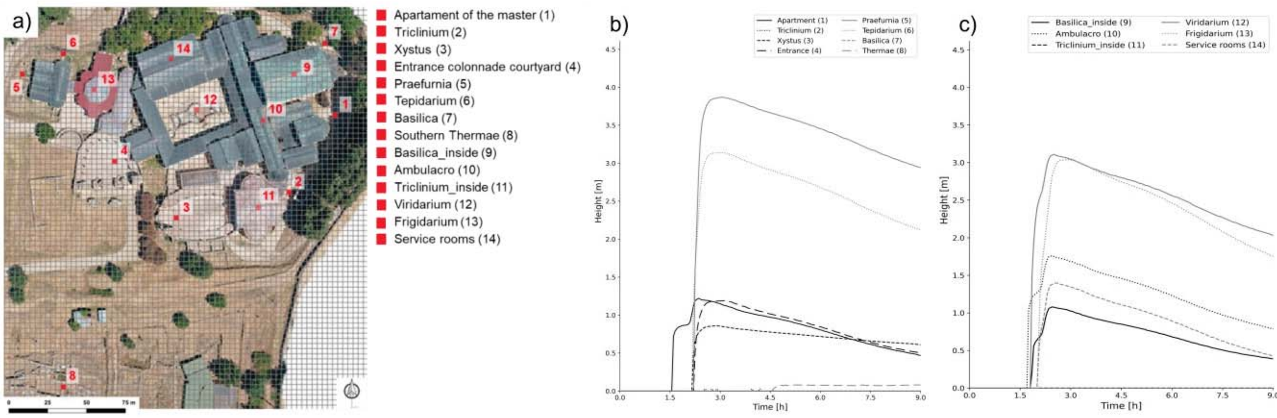

Figure 3: (a) position of the control cells, inside and outside of the archaeological area for "open Villa" model (b) trend of the heights of the debris flow for one of the simulations in outside control cells (c) trend of the heights of the debris flow for one of the simulations in inside control cells.

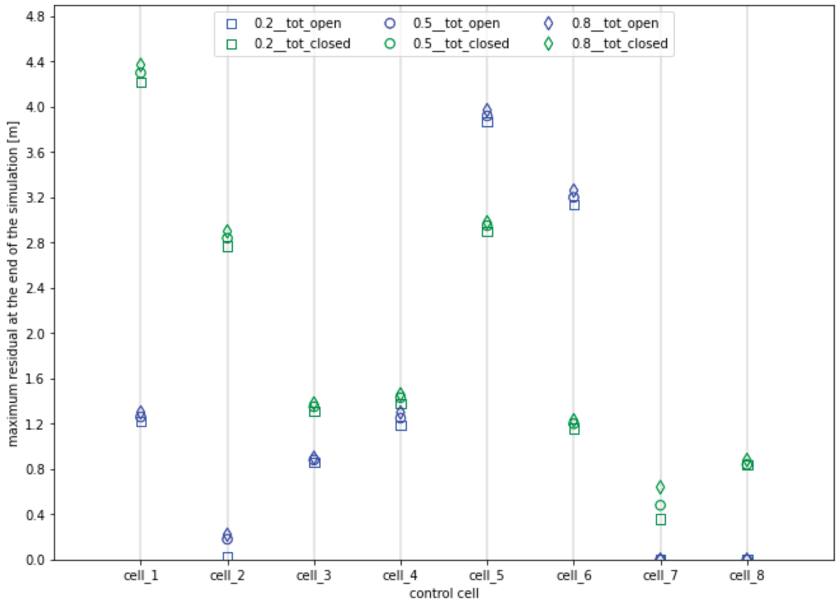

Figure 4: Comparison between the maximum value of the debris tie on the control cells outside the Villa, for the two numerical models with the Villa open and closed

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