The Greenstream: Geological hazards to a submarine pipeline.

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Abstract

Submarine geologic hazards are a natural phenomenon that is part of the evolutionary process of our planet. Although they do not cause as many casualties per year as other natural disasters, such as landslides or floods, they may generate catastrophic events with a high number of casualties and enormous economic loses both at short and long term. Therefore, they have to be taken into account due to the human expansion, which is larger day after day, occupying territories exposed to submarine hazards.

With the aim of bringing gas from Libya to Sicily, the Italian company ENI built a submarine pipeline: the Greenstream, located in the Sicily channel in the central Mediterranean. The intense tectonics has produced a series of structures that, if reactivated, may pose a threat to the stability of the pipeline or any other underwater structure made within this context. This justifies the development of a hazard analysis of all elements that could create a hazard for such construction. For this reason an initial study has been done both in a qualitative and quantitative ways. The first consisted in developing a map based on the interpretation of geomorphological structures from the seafloor bathymetry and a hill shade map. For the second analysis geotechnical data from reports written prior to the construction of the pipeline were added, allowing the making of a map with the safety factor along the pipeline route. These two evaluations, qualitative and quantitative, contribute to a first approach to hazard assessment along the Greenstream pipeline.

Keywords: geological hazards, Sicily channel, Greenstream pipeline, qualitative analysis, quantitative analysis.
1. Introduction

Marine geohazards are geological conditions at the sea floor or within sub-bottom sediments that, if unrecognized, could result in dangerous or catastrophic events with attendant risks to life and/or infrastructure.

Ocean hazard events like tsunamis, triggered by earthquakes and landslides, storm surges associated with hurricanes and extreme storms, oil and gas spills, floods and associated watershed contaminants, affect the health and safety of our Nation's ocean and coastal communities and ecosystems. For that reason it’s important to study the causes, distribution and hazard potential of coastal and submarine hazard events including earthquakes and submarine landslides, as well as associated tsunami potential; coastal inundation associated with hurricanes, extreme storms, and sea-level rise; oil and gas spills; along with model development to help evaluate and forecast coastal hazard probability and occurrence.

Scientific knowledge of the severity and frequency of re-occurrence of these marine geohazards enables mitigation of the risk to communities, infrastructure and the environment. Regulatory agencies need this information for managing the development of offshore oil and gas resources.

The consideration of catastrophic events is a function of the effects on the environment, mainly to the biosphere, and more important if they affect directly the human population and its immediate environment. (Font 1996)

Every year as the human population grows; areas are being built upon, where previously it has been impossible to build any structure. This demographic expansion has led to the construction of structures on the seabed or the ocean, taking the level of vulnerability to a higher level. A clear example of this fact is the Greenstream pipeline.

2. The Greenstream pipeline

The Greenstream project (Libyan Gas Transmission System LGTS) is part of the Western Libyan Gas Project and includes the Mellitah Compressor Station, on the Libyan coast, the underwater gas pipeline and the Reception Terminal at Gela, in Sicily (Figure 1).

The Greenstream pipeline started with the idea of transferring natural gas from Libya to Italy in the 1970s. Feasibility studies were carried out in the 1980s and 1990s. Finally the construction of the pipeline began in August 2003; laying activities lasted for about six months and were concluded in February 2004.

The Greenstream pipeline was the longest underwater pipeline ever laid in the Mediterranean Sea, it has a diameter of 32", and it’s around 520 kilometers long and crosses the sea at points where the depth reaches more than 1000 meters. The pipeline had an initial capacity of 8 billion cubic meters (bcm) of natural gas per year. Later the capacity was increased to 11 bcm.

This structure will be subject to the full range of geological risks that develop in the ocean such as slope failures associated to landslides, subseafloor fluid escape features such as pockmarks and shallow faults from recent tectonic activity.

This structure will be subject to the full range of geological risks that develop in the ocean such as slope failures associated to landslides, pockmarks associated to a fluid scape and shallow faults associated to a recent tectonic activity.

3. Objectives

The objectives of this work have been focused on understanding the hazards that may affect a submarine pipeline. To achieve this objective a map of the hazard to the pipeline will be elaborated including all features and structures detected and a series of maps representing the factor of safety to slope failure along the pipeline route. The latter
Marc Pascual: “The Greenstream: Geological hazards to a submarine pipeline”

maps will use geotechnical measurements extracted from the project report. For the elaboration of the map with all the features will be obtained information about the structural elements and how they can affect a submarine piping. The spatial distribution of this elements and their morphological characteristics will determine areas with more or less probability of an active risk for the pipeline. The map extracted from the geotechnical measurements will allow us to understand the distribution of the safety factor along the pipeline, and how this can affect the stability of this structure. These analysis together will introduce the idea of the hazard level along the pipeline path.

4. Geological setting

The Sicily channel is located in the central Mediterranean region, to the north of the African continental plate (Burollet et al. 1978). This region is controlled by the Pelagian platform to the north (Micallef, Berndt, Debono, 2011) and the Tripolitania platform to the south (Capitano et al. 2011), and all the area is a compressional tectonic system from southern Sicily island to North-West Libya (Boccaletti, Cello, Tortorici. 1987) (Figure 2).

The Pelagian platform is characterized by thrust faulting at its northern and western margins, and fault-controlled rift basins of Miocene-Pliocene age in its center (Reuther and Eisbacher, 1985). The eastern margin is separated from a deeper Ionian Basin by the Malta Escarpment (Argnani & Bonazzi 2005). The Sicily Channel has been affected by continental rifting processes during the Neogene-Quaternary (Finetti, 1984). This rift system created several geologic features and NW trending basins named, Gela basin, Pantelleria graben, Malta graben and Linosa graben. (Figure 3). (D. Minisini et. al 2007). These basins have been active since the early Pliocene. (Corti et. al. 2006).

The presence of a rift environment in a foreland area in front of a collisional belt is not a common tectonic scenario. Besides, there is not a plenty geophysical dataset in the Sicily channel, in consequence has been impeded a detailed morphostructural area of this region (Civile & Ledolo 2010).

According to the pipeline way, the most interesting areas of study are the Gela basin (GB), the Malta Graben (MG) and the Linosa Graben (LG) (Figure 3).

Figure 2 Tectonic setting of Sicily cannal area (from Corti et al., 2006). Pliocene–Pleistocene tectonics is marked both by the ENE-trending Maghrebides-Sicily-Apennines accretionary prism and by contemporaneous NW-trending rift. The black and red arrows indicate the direction of compression and extension, respectively. The stars indicate the main volcanic centers of Linosa and Pantelleria. AP—Adventure plateau; GB—Graham Bank; NB—Nameless Bank.

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Figure 3 Bathymetric setting of the pipeline path. Gela basin GB, Malta Graben MG and Linosa Graben LG.
Marc Pascual: “The Greenstream: Geological hazards to a submarine pipeline”

This zones have hard depressions and several depth changes. The tectonic activity of this area generated volcanic events generated the formation of the Linosa Island. On the other hand the Tripolitanian platform has a plane morphology with a gradual depth change and without complex structures (Appolonia 2002).

The Gela basin is an area of multiple slope failures during the late – Quaternary (Minisini. 2007). One of the evidences of these slides is the presence of two big slide deposits (Minisini. 2006). The total area of the Gela slide and associated debris flow transport has been estimated around 1500 km2 (F. Trincardi. 1990).

The Maltese graben system is a series of Miocene–Quaternary extensional basins located in the foreland of the Sicilian Apennine–Maghrebian fold and thrust belt (Dart. 1993). The maximum depth reaches more than of 1200 meters in the deepest parts of this Graben (Claus-Dieter 2007).

The Linosa graben formed as a consequence of a prominent right-transpressive shear motion accompanied by a significant crustal thinning and mantle uplift (Finetti 2005). Characterized by the presence of volcanic activity, dated from 300-350 ka to present (Argani 2009). This graben complex reaches a maximum depth around 1000 m (Claus-Dieter 2007).

5. Methodology

5.1 Dataset.

The digital dataset used in this work has been obtained from D’appolonia reports and a Gas survey Ltd reports offering multibeam bathymetric data, Cone penetration test (CPTs) and Piston core (Pc) dataset information.

Gardline Surveys Ltd was contracted by ENI Divisione Agip to undertake a pipeline route survey for the Libya Gas Transmission System in the Mediterranean Sea. Before the construction of the pipeline this company has been responsible of all the geophysical information used for this work. Gardline surveys provided an exhaustive analysis that has been consulted for this work.

The survey requirements were to acquire, process, interpret and report upon detailed hydrographic, geophysical and geotechnical data along a pipeline route between Libya and Sicily and to the west of Malta. The main objectives were to provide bathymetric, morphological and physical information on the seabed and shallow soils along the route corridor defined between two previously surveyed intersection points.

5.1.1 Multibeam Bathymetric data.

For the multibeam bathymetric data were used 3 different echo sounder multibeam systems. The principal characteristics of this echo sounders can be observed in the calibration tables (Figures 4, 5 and 6).

- ELAC 40 Hz

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>ELAC 50Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transducer mount</td>
<td>Hull mounted through moon pool</td>
</tr>
<tr>
<td>Motion reference unit</td>
<td>SEATEX MARUS</td>
</tr>
<tr>
<td>Sound velocity probe</td>
<td>SYP+</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Parameters</td>
<td></td>
</tr>
<tr>
<td>Transducer Frequency</td>
<td>50kHz</td>
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<tr>
<td>Offset from Reference Point</td>
<td>$x = -1.75m$ $y = +12.70m$</td>
</tr>
<tr>
<td>Acquisition software</td>
<td>Bottom Chev Compas</td>
</tr>
<tr>
<td>Velocity Sensor at Tsd</td>
<td>N/A</td>
</tr>
<tr>
<td>General water depth</td>
<td>42m – 1075m</td>
</tr>
<tr>
<td>Average ship’s speed</td>
<td>9 knots (3m/s)</td>
</tr>
<tr>
<td>Mode</td>
<td>Mekhans</td>
</tr>
<tr>
<td>Angular coverage</td>
<td>128° – 100°</td>
</tr>
<tr>
<td>Horizontal coverage</td>
<td>4.1 – 5.5 x depth</td>
</tr>
<tr>
<td>No. of beams</td>
<td>108 – 66 equi-distant spacing</td>
</tr>
<tr>
<td>Cross track beam spacing</td>
<td>1.25° (1.6° beam)</td>
</tr>
<tr>
<td>Ping rate</td>
<td>Speed Dependent</td>
</tr>
<tr>
<td>Along track beam spacing</td>
<td>Speed Dependent</td>
</tr>
</tbody>
</table>

Figure 4. ELAC 50 Hz echo sounder. At this table can be observed their characteristics. This system has been used to provide a swathe bathymetry data

- Simrad EM100
Marc Pascual: “The Greenstream: Geological hazards to a submarine pipeline”

Figure 5. Simrad Em1000 echo sounder. At this table can be observed their characteristics. This system has been used to provide a swathe bathymetry data.

Table: Instrumentation

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Value</th>
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</thead>
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<td>Multibeam echo sounder</td>
<td>Simrad EM1000</td>
</tr>
<tr>
<td>Transducer mount</td>
<td>Hull mounted through moon pool</td>
</tr>
<tr>
<td>Motion reference unit</td>
<td>MIPUS</td>
</tr>
<tr>
<td>Sound velocity probe</td>
<td>SWP+</td>
</tr>
</tbody>
</table>

Figure 6. Reason SeaBat 8101 echo sounder. At this table can be observed their characteristics. This system has been used at deep water sections.

Table: Instrumentation

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multibeam echo sounder</td>
<td>Reason SeaBat 8101</td>
</tr>
<tr>
<td>Transducer mount</td>
<td>FOCUS 400 R3UK 1003 RDTV</td>
</tr>
<tr>
<td>Motion reference unit</td>
<td>DMS 2-05</td>
</tr>
<tr>
<td>Sound velocity probe</td>
<td>SWP+</td>
</tr>
</tbody>
</table>

Operating Parameters

- Transducer Frequency: 95kHz
- Offset from Reference Point: x = -1.75m, y = +12.70m
- Acquisition software: Simrad Meridian
- Velocity Sensor at Tid: Off
- General water depth: 42m - 1079m
- Average ship’s speed: 4 knots (2m/s)
- Node: EODSA (Degrees vary)
- Angular coverage: Depth Dependent
- Horizontal coverage: 4.1 x depth
- No of beams: 48/66 equal/distant spacing
- Cross track beam spacing: 3.4% depth
- Ping rate: Speed Dependent
- Along track beam spacing: Speed Dependent

Calibration

- Date: 15.06.99
- Description of method: Field calibration, offshore Malta
- Transducer alignment: -0.2° (determined in dry dock)
- Gyrocompass correction: -0.14°
- Pitch correction: -0.42°
- Roll correction: +0.45°
- Time delay: 0.5s (determined by dry calibration)

Figure 5. Simrad Em1000 echo sounder. At this table can be observed their characteristics. This system has been used to provide a swathe bathymetry data.

Data for the entire project were processed in accordance with the specifications prior to providing Digital Terrain Models (DTM). The processing routines for the different swathe systems were of a similar nature.

Water depths were reduced to mean sea level from predicted tidal heights at the El Boui and Gela basin Platform. Both tide gauge positions extrapolated to site. A first pass of editing routine was initially applied ensuring that no real seabed features were removed.

During the reconnaissance phases, the soundings for each of the areas, and for the routes between the areas, were treated separately, and models for each section were produced.

During the detailed geophysical survey, the multibeam data were acquired in 25 km segments; these were split into segments and edge matched where they overlapped. Each DTM overlaps its adjacent one by 10-20m.

For final production of bathymetry and contours, the multibeam data were gridded into a 25 m x 25 m Digital Terrain Model (DTM) for the Reconnaissance Surveys. For the Detailed Geophysical Survey either 5 m x 5 m or 10 m x 10 m DTMs were used (depending on topography and specified onboard by the Client Representative). The default filtering and smoothing processes within GeoSea's IRAP/floor software were then applied.

Generally, the multibeam data were of a high quality although ray dipping was noted at the outer edge of both beams on the ELAC system due to the transducer housing problems experienced. The other beams were eliminated in processing. The comparison checks against the single beam data were also good and showed that accuracies were within the error budget specified for the survey.

Seabed profiles for each section were also produced using the EM 1000 data. The Rosen Sea bathymetric data provided seabed profiles for the deep water sections of the route.

5.1.2 Cone penetration test (CPT) data.

The CPT test was carried out with the Gardline GTEC-1 system. GTEC-1 is capable of carrying out in situ testing in water depths of up to 2,000 meters. Their characteristics can be observed in Figure 7.
The system uses a combination of a subsea automated control unit, subsea power packs, and acoustic telemetry to provide a compact, single cable system suited to a variety of applications.

The Cone Penetration Test is based on pushing an instrumented cone into the ground at a constant speed, with continuous measurement of the cone end resistance, the friction along the sleeve of the cone, and the pore water pressure. These measurements make it possible to evaluate accurately the ground conditions and stratigraphy over the penetrated depth.

Full data sets can either be up-linked between tests or downloaded each time the subsea module is returned to the vessel. The onboard data processing system enables all data to be processed and interpreted onboard, substantially reducing reporting times and enabling the onboard team to optimise the survey plan.

On the next image (Figure 8) can be observed the distribution of all this measures along the pipeline path and a classification between the Cone penetration tests and the Piston core sample.

5.1.3 Sediment samples.

The seabed was sampled by means of a Kullenberg Piston Corer. This corer has a core barrel length of 3 meters, a core diameter of 8.5 cm and can work at different water depths. These samples were used to assist interpretation of sonar and shallow geophysical data and ascertain the geotechnical properties of the shallow soils.

Core recovery varied between 0.3 and 3.0 meters with an average of about 2.0m. This compares with core penetration of up to 3.0 meters as determined from sediment sticking to the outside of the core barrel.

Core samples were recorded and measured immediately after recovery and cohesive material from each end was saved as simple compression test and undrained shear strengths by penetrometer and vane shear respectively. Whenever practicable cores were stored upright and, to this end, were sawn into sections of approximate maximum length 1 meter.

5.2 Interpretation of seafloor structures.

During this work an interpretation of the different morphologic structures of the seafloor that could develop in geohazards has been carried out. In this section the criteria used for the recognition and analysis of these structures are described.

The identification and mapping has been carried out using ArcGIS 10.1 Geographic Information Systems (ArcGIS ®).

The bathymetric dataset was loaded in different segments, for easier handling and merged with the ArcGIS mosaic tool (data management). The result has been a 520 km x 700 m bathymetric layer that contains all the bathymetric data.

During this process it was found that some areas were missing the bathymetric dataset information. These areas were not included in the merged bathymetry and remain as “no data” areas.

During elaboration of the qualitative geohazard map a basic hillshade map or a grey scale shaded relief map that allows the immediate understanding of landforms, thus highlighting geomorphic or
structural elements that could not be easily identified, has been used. To further facilitate the identification of geohazard features as well as for use as input into slope stability analysis a slope map has also been created using, the ArcGIS slope function in Spatial Analyst. The slope map has been created individually on each of the 25 km sections of the pipeline route.

The ArcGIS project, loaded data and the files created from these, have been georeferenced with the coordinate’s system: _UTM Zone 33, ellipsoid WGS 1984.

5.2.1 Pockmarks

The first structural element interpreted during this work have been the pockmarks distributed along the pipeline way. Pockmarks are sub-circular depressions of variable size and depth that appear at the seafloor with a large variability of sizes and depths. (Taviani, 2003).

Pockmarks often appear clustered in some areas and cover wide zones, representing a common and widespread feature on the continental margins worldwide (Hovland and Judd, 1992). Sometimes pockmarks can be found isolated or in small groups aligned (King y MacLean, 1970; Hovland, 1984) and appear typically in unconsolidated fine-grained sediment, likely clays or sands (King and McLean, 1970).

They have a strong importance, especially because they are generated by fluids escaping from deeper levels and these fluids are often hydrocarbon enriched. Fluid escape may occur in the form of slow seepage, vigorous venting or even eruptions (Tiviani, M, 2003). Pockmarks can be an important geohazard for offshore constructions and navigation due to the instability generated to the structures by the constant fluid scape (Newton et al., 1980; Hovland, 1987; Curzi et al., 1988) and can significantly alter the geotechnical characteristics of the sediment (Sills and Wheeler, 1992).

The pockmark interpretation has been done with the conjunction the hillshade layer and the bathymetric layer, due the high resolution of both layers. The slope gradient map and slope changes are represented by a color scale. Red color indicates a steep slope while grading to green indicates a gentler slope. With the slope map created superposed on the grey scale hillshade map, pockmarks are highlighted appearing as red rounded spots surrounded by green. (Figure 9).

On completion of the pockmark interpretation, an analysis with the ArcGIS spatial analyst tool was done. The pockmark statistics are shown as a table. An interpretation of the results and the bathymetric dataset has been used for this analysis. (Table 1). The pockmarks number it’s an identificative of the order of identification of every pockmark. Being 1 the first one interpreted until the pockmark 812, the last one.

When the pockmarks area was smaller than the cell of the bathymetric raster, these pockmarks couldn’t be detected by the analyst tool.

![Figure 9](image-url) Pockmark field. Slope layer superposed to the hillshade layer. The red spots are asly recognizable.

<table>
<thead>
<tr>
<th>Pockmark</th>
<th>AREA</th>
<th>MIN</th>
<th>MAX</th>
<th>RANGE</th>
<th>MEAN</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7100</td>
<td>376,62</td>
<td>384,00</td>
<td>7,38</td>
<td>380,37</td>
<td>1,75</td>
</tr>
<tr>
<td>2</td>
<td>25900</td>
<td>513,50</td>
<td>527,21</td>
<td>13,70</td>
<td>521,29</td>
<td>3,21</td>
</tr>
<tr>
<td>3</td>
<td>1800</td>
<td>384,07</td>
<td>386,30</td>
<td>2,23</td>
<td>385,43</td>
<td>0,72</td>
</tr>
<tr>
<td>4</td>
<td>4500</td>
<td>370,40</td>
<td>375,46</td>
<td>5,06</td>
<td>373,53</td>
<td>1,45</td>
</tr>
<tr>
<td>5</td>
<td>1800</td>
<td>330,85</td>
<td>332,87</td>
<td>2,02</td>
<td>331,80</td>
<td>0,61</td>
</tr>
<tr>
<td>6</td>
<td>2800</td>
<td>330,92</td>
<td>332,48</td>
<td>1,57</td>
<td>331,53</td>
<td>0,45</td>
</tr>
<tr>
<td>7</td>
<td>3800</td>
<td>327,67</td>
<td>329,75</td>
<td>2,08</td>
<td>328,65</td>
<td>0,61</td>
</tr>
<tr>
<td>8</td>
<td>3500</td>
<td>327,41</td>
<td>330,14</td>
<td>2,73</td>
<td>328,33</td>
<td>0,77</td>
</tr>
</tbody>
</table>

Table 1 Pockmark tabl example; AREA: pockmark’s area (m²), MIN: minimum depth (m), MAX: maximum depth (m), RANGE: total pockmark depth (m), MEAN: mean pockmark depth (m), STD: pockmark roughness.
5.2.2 Scarps

The second structural element that was identified during this work is the distribution of scarps along the path of the pipeline.

These scarps are linear structures with an undefined length that can go from meters to hundreds of meters in this area. The main characteristic used to recognize them is the presence of slope changes including sharp and softer changes in slope gradient.

The slope changes can affect the pipeline inducing suspended sections and they are an indication of ancient slope failures or the presence of a fault system. Ancient slope failure areas may be suitable to a new landslide episode. When a fault occurs, it results in a tectonic event which causes fractures to the lower levels of seafloor (Matt et al. 2011) and may also cause disruptions to seafloor structures. Considering this fact, the edges identified have been classified in two groups: fault scarps and landslide heads. After the first classification, the edges have been classified into soft or hard edges (Figure 10) indicative of ancient or recent features respectively.

The criteria used to differentiate between these two groups have been done using all the morphological forms associated to landslide heads or fault scarps. All the fault scarps have been considered as a slope change in a relatively plane area and with straight lined edges (Figure 11). The landslide heads have been identified as a slope change with a half circled line edges morphology. Besides the edge, the presence of a landslide deposit with a covering an area at the bottom of the edges has used as a criteria for the recognition of the landslide heads (Figure 11).

The interpretation of the Edges has been mainly performed in the grey scale hillshade map in conjunction with the bathymetric and slope map. It was often difficult to identify the slope direction of some areas and for this reason, a bathymetric contour map on each one of the 25km sections of the pipeline route was also elaborated.

Once the scarps interpretation was finished, an analysis with the ArcGIS spatial analyst tool was done. The statistics on the edges were obtained (Table 2). The interpretation and the bathymetric dataset has been used for this analysis. (Table 2) (Table 3). The number of the scarps determine the order of identification of this scarps, being 1 the first one identified until the number 298, the last one.

<table>
<thead>
<tr>
<th>Scarp</th>
<th>TYPE</th>
<th>SLOPE</th>
<th>MIN</th>
<th>MAX</th>
<th>MEAN</th>
</tr>
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<tbody>
<tr>
<td>1 Landslide head</td>
<td>hard</td>
<td>201.60</td>
<td>215.04</td>
<td>207.82</td>
<td></td>
</tr>
<tr>
<td>2   Fault scarp</td>
<td>soft</td>
<td>128.19</td>
<td>129.39</td>
<td>128.86</td>
<td></td>
</tr>
<tr>
<td>3 Landslide head</td>
<td>soft</td>
<td>852.22</td>
<td>859.45</td>
<td>855.82</td>
<td></td>
</tr>
<tr>
<td>4 Landslide head</td>
<td>hard</td>
<td>875.49</td>
<td>876.04</td>
<td>875.83</td>
<td></td>
</tr>
<tr>
<td>5 Landslide head</td>
<td>soft</td>
<td>819.37</td>
<td>820.93</td>
<td>820.11</td>
<td></td>
</tr>
<tr>
<td>6 Landslide head</td>
<td>hard</td>
<td>851.20</td>
<td>858.24</td>
<td>854.68</td>
<td></td>
</tr>
<tr>
<td>7 Fault scarp</td>
<td>hard</td>
<td>478.83</td>
<td>488.99</td>
<td>484.17</td>
<td></td>
</tr>
</tbody>
</table>

Table. 2 Scarp example table; TYPE: classification of scarp, SLOPE: classification of the slope, MIN: minimum depth (m), MAX: maximum depth (m), MEAN: average slope depth.
Marc Pascual: “The Greenstream: Geological hazards to a submarine pipeline”

Table 3 Scarp table example; SLength: total length of the edge (m), Min slope: Minimum slope of the edge, Max slope: maximum slope of the edge, Avg slope: average total slope.

<table>
<thead>
<tr>
<th>EDGE</th>
<th>SLength</th>
<th>Min_Slope</th>
<th>Max_Slope</th>
<th>Avg_Slope</th>
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<tbody>
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<td>6.22</td>
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<td>1.24</td>
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</table>

Due to the missing bathymetric dataset at some areas of the pipeline path, the analysis couldn’t be done for all the edges. Another problem presented during this operation is that some edges are larger than the bathymetric shape. That edges won’t have a representative value of the real edge length.

5.2.3 Other structures

During the accurate seafloor analysis, additional seafloor structures were interpreted and identified. These can be seen along the Greenstream path and may also pose a hazard to the pipeline. These forms have been found in lesser amounts compared to pockmarks and scarps. For this reason they have been described in a different section. Here the various landforms identified and the criteria used for their recognition are described in detail.

The structures identified are:

- **Bedforms**: Bedforms include a wide-spectrum of morphologies of large-scale flow-transverse structures, they all occupy a similar position in the lower-flow-regime sequence between ripples and upper plane bed. The wide variety of forms is a reflection of secondary effects such as channelization, fluctuating water levels, and unsteady and reversing flows. (Gail and Ashley 1990)

- **Ridges**: Ridges are structures identified from scarps, with the particularity of having more than one scarp. These scarps have to be in different direction, generating an elevated area that distinct both scarps.

- **Gullies**: Submarine gullies are small-scale, straight, shallow channels formed in relatively high seafloor-slope. The long term evolution of these structures may lead to submarine canyons. The mechanisms associated with the origin and evolution of submarine gullies are, however, still poorly defined (Michalef et al. 2010).

- **Rockbed**: Rockbed forms are rocky bodies which outcrop due to the erosion by ocean currents in the upper layers. These hard rock masses have been identified from their relatively high roughness, and the occurrence of strong depth changes. This rocky masses are usually found isolated and with a moat associated to their limits.

- **Moats**: Moats are depressions associated to the bedrocks. These structures are formed when a submarine current hits bedrock, this current will deflect to the sides, speed up and generate erosion of the seafloor, especially if the seafloor is made of soft soil. The erosion will generate small depressed areas with little sedimentation surrounding the bedrock form.

- **Landslide deposits**: These deposits have been used as a criterion for the identification of the landslide heads. Landslide deposits have a range of shapes, but all of them present three distinct parts, the landslide top (the highest point of contact between the displaced material and the main scarp.), the main body (the part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface of rupture.) and the toe (the lower, usually curved margin of the displaced material of a landslide; it is the most distal from the main scarp).

5.2.4 The Twin slide Gela basin area

Several samples were taken in the Gela basin zone (Figure 12), where no bathymetric data was available for this study. This basin is a 20 km wide and up to 50 km long with water depth between 600 and 700 meters. (Trincardi and Argnani 1990).
Previous studies have determined the presence of an old submarine landslide and two more recently exposed landslides known as the southern and northern Twin slides (Figure 12) (Minisini et. al. 2007). These giant mass-transport features commonly record multiple phases of failure and result in rather thick and complex deposits within which it proves difficult to define their internal structure (Locat & Lee, 2002). The hazard to the pipeline, was a new landslide of similar dimensions to occur in this area, is significant. This area shows a chaotic sea floor morphology formed by different landslide scars, old hummocky landslide deposits, and a lot of different structures like gullies and pockmarks. (Minisini et. al. 2007). For these reasons it has been considered advisable to carry out an analysis of this area too.

This analysis will not be subject of the quantitative analysis carried out for the remaining Greenstream pipeline path, as the slope gradients at the base of such analysis, will not be available. Despite the absence of a bathymetric dataset of this area, it has still been possible to extract a hillshade slope map in color from a previous work (Figure 13) (Minisini et. al. 2007).

This area has been added to the ArcGIS analysis project used during this work. The georeferencing had been done comparing this area with a similar georeferenced map of the same area.

Once verified that there was not a strong deformation and the geographical location was as accurately as possible, the interpretation of the different morphological structures of this area has also been carried out.

5.3 Geotechnical properties.

In order to perform the quantitative hazard analysis against seafloor failure along the pipeline path, geotechnical measurements acquired during the Gas and d’Appolonia surveys have been digitized.

The locations where CPTs and piston cores were taken have been georeferenced and introduced into the ArcGIS project (Figure 8). Once georeferenced a review of all the geotechnical information contained in the reports has been performed and the relevant measurements have been introduced in ArcGIS. The data introduced contains information about measured geotechnical parameters both from the sediment samples obtained from piston cores as well as from the CPTs. Besides the geotechnical data, surface lithology and predominant lithology information was also entered in the GIS project, as well as a preliminary interpretation of the structures observed by d’Appolonia (see annex 1, Tables, from the supporting information).

During this process of storing and sorting geotechnical measurements and lithological information a variety of problems has been found (e.g., dealing with different data types, sampling resolution and depth intervals, some areas had low sample and test density for the calculations in quantitative hazard analysis. Collection of these data in a georeferenced way and with the help of mathematical functions within the Spatial Analysit module of ArcGIS Geographic Information Systems (ArcGIS ®), a series of safety factor maps was produced.

5.4 Quantitative analysis and security factor map.

The parameters used for the creation of the safety factor map are based on shear strength gradients with depth, the wet bulk density measurements and the slope angle map. For a better understanding of how the slope stability may change according to loading conditions the safety factor and has been calculated for different situations.

5.4.1 Drained safety map (infinite slope analysis)

The factor of safety (F) is defined as the ratio of

\[ F_s = \frac{\tan \phi}{\tan \beta} \]

Equation 1. Safety factor for drained soils (Fs)
shear strength to shear stress required to maintain stability. For the drained safety factor map and assuming cohesionless sediments, the factor sediment reduces to the following formula:

For an infinite slope analysis, the FS is independent of the slope depth, and depends only on the angle of internal friction, $\phi$, and the angle of the slope, $\beta$. The slope is said to have reached limit equilibrium when the $F_{s}=1.0$. Also, at a $F_{s}=1.0$, the maximum slope angle will be limited to the angle of internal friction, $\phi$.

The angle of internal friction ($\beta$) has been obtained from direct shear strength testing resulting in a friction angle between 40º and 45º.

The slope angle ($\beta$) is the continuous slope map layer created during this work that contains a min value of 0º and a maximum value of 75º. This maximum value of 75º only is reached occasionally at some points, where the scarps identified are situated, (Graben areas) or where bedrock out-forms appear. In general this pipeline path has slope angles between 0º and 10º.

The result of these calculations have allowed to generate a map with the safety factor along the path of the pipeline in drained conditions. This map can be used as a first approximation for the long-term slope stability of the seafloor along the pipeline path.

5.4.2 Undrained safety factor map (infinite slope analysis)

For the undrained safety map the following formula has been used:

$$ F_{s} = \frac{c}{\gamma_{sat} H \cos^{2} \beta \tan \beta} $$

Equation 2. Safety factor for undrained soils

The parameters used for this equation are the undrained shear strength ($c$), the saturated soil unit weight ($\gamma$), and the slope angle ($\beta$).

The shear strength values have been determined from measurements of shear strength in sediment cores as well as from CPT data. In order to obtain measurements at the same depth intervals an undrained shear strength gradient approach has been used.

The depths chosen are 1 meter, 2 meters and 5 meters depth below sea floor. These depths were chosen because they are considered representative of shallow slope failures that may occur in the area and because the amount of data allowed the analysis at these depth intervals.

Needless to say, the amount of data for the calculation decreases with depth, so the accuracy of the hazard map developed also diminishes with depth.

Of 141 piston cores and CPTs, 77 had information for the calculation of the shear strength at $c=1$ meter. In addition, the distance between the data points at this depth is similar, and facilitated the creation of a more accurate grid (Figure 14).

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By obtaining the ($c$) at depths of 1 m, 2 m and 5 m below sea floor a grid was created for each depth along the Greenstream path.

Wet density values used to derive the soil unit weight have been extracted from piston core samples. The different measures of the wet density at different depths show no consistent trend with depth and a mean wet density of 1,6724 g/cm$^3$ (1672.4 kg/m$^3$) is assumed for the upper 5 m (Figure 15). In this case however the maximum depth measurements are limited to 2.5 meters.
Graphic 1 also shows that the coefficient of correlation is rather low. The coefficient of determination is far closer to 1. The value of 1.6724 g/cm³ has been adopted as a mean for the generation of the safety factor map. That density value times gravity (9.8 m/s²) allows to obtain the saturated soil unit weight (Equation 3).

\[ \gamma = \rho g \]

Equation 3. Saturated soil unit weight

The resulting saturated soil unit weight has been: 1638952 N/m³

The value of H is the depth at which the analysis will be carried out, in this case 1 m, 2 m and 5 m below sea floor, according with the c values calculated previously.

The final result of these calculations will be a grid with the safety factor along the path of the pipeline in undrained conditions at 1 meter depth, 2 meters depth and 5 meters depth

6. Results

The results obtained from the qualitative and the quantitative determine an approximation of the hazard that can affect the pipeline. The qualitative interpretation will expose the identified morphological features, in this case pockmarks and Scarps, and the relation with the hazard. The quantitative analysis based on the geophysical measures will allow the calculation of the safety factor value along the pipeline path.

6.1 Qualitative analysis

Due to find a relation between the morphological characteristics of the structures detected has been realized an independent analysis for the structures founded. This analysis will allow an interpretation of the principal causes that can relation this different structures.

6.1.1 Pockmarks

In this study 812 pockmarks have been found. These pockmarks have a mean area of 13529 m². Figure 16A shows the depth with respect to surrounding seafloor (m) distribution of the pockmarks along the Greenstream path. The maximum depth is close to 50 m and the minimum value 0.13 m. It can be observed that most pockmarks have depths ranging between 0.13 and 10 meters. The number of pockmarks with larger depths decreases exponentially as the depth value increases with a final maximum depth of 50 meters.

Figure 16B shows the relation between pockmarks’ area (m²) and depth with respect to surrounding seafloor (m). In this Figure can be has been done a classification of the pockmarks founded by the depth (m) where they have been identified the largest pockmarks are close to 500000 m² while the minimum area is 200 m². It is important to remark that pockmarks with an area less than 100 m² could not be analyzed because the cell size of the raster used (10m x 10m) is bigger than the pockmark identified. It can be observed however that most pockmarks with areas between 0 and 50000 m² have depth values below the 20 m. Overall, despite large scatter in the data, it can be seen that pockmarks larger than 150000 m² show increasing pockmark depression depth. Small pockmark structures can reach up to a certain depth, in this case 30 m, but for larger pockmarks there is not a specific range of values going from less than 20 meters to more than 45m. The depth of this pockmarks has a relation with their area and their depth with the surroundings. Can be observed how most of pockmarks are have areas smaller than 50000m² and a depth respect to the surrounding smaller than 15 m independently from...
the depth. But, can be observed how pockmarks with the bigger areas or large depth respect the surroundings are situated at depths between 500 and 630 (represented by a square). Other pockmarks founded at different depths only can be founded at the small range of the bottom left of this figure.

Figure 16C shows the relation between the amount of pockmarks and the STD coefficient. This coefficient is intrinsically related with the roughness of the pockmark base. It can be observed that most of the pockmarks identified have a STD coefficient between 0 and 2, indicating a relatively even surface. The maximum STD value is 12.2.

Figure 16D shows the relation between the pockmarks area (m²) and the bathymetric depth (m) at which they occur along the pipeline path. The maximum pockmarks depth is around 1100 meters and the minimum depth shallower than 200 meters. In this case, a pattern of distribution where the majority of pockmarks are clustered between 400 and 800 meters can be seen. Most importantly, is the fact that pockmarks with the larger areas...
only appear within this range, suggesting that they cannot be formed at shallow depth or at deep levels, or that the structures that generate that pockmarks only can be found at these depth range.

6.1.2 Scarp analysis

During this work, 297 edges with a mean length of 1038 m have been found. From this, 240 have been interpreted as fault scarps and 57 as landslide heads. 187 soft scarps and 110 hard edges have been detected from the total value. Presented in the following, are graphics realized for a better analysis of this morphological structures.

Figure 17 shows the relation between the amount of scarps interpreted and the depth where they occur. It can be seen that the scarps are distributed in a full range of depths between 120 meters and 1200 meters. It can also be observed that the most scarps are located between the 600 m and 800 m depth range. It is important to remember that the areas without a bathymetric dataset use a depth value of 0 meters that hasn’t been represented on this figure. For that reason, couldn’t be represented all the Scarps detected during this work.

Fault scarps can be found in a wide range of depths, while landslide heads are concentrated at depths between 600 and 800 meters. Landslide heads reach a maximum length of 2500 meters and are generally shorter than fault scarps.

6.1.3 Qualitative hazard map

The qualitative hazard map revealed the situation of the morphological features during the pipeline path. As an example of the identification done are presented some figures of the interpretation realized. The figures presented are representative from the structures founded and are disposed from North to South.
Figure 19 shows an area where can be observed different morphological features. This area can be found between 200 and 300 meters depth. The first one interpreted in this section have been the bedrock out forms that are distributed at the center. This bedrock out forms only appear at this area of the pipeline path, and have been identified because of the characteristic roughness of the hillshade map. This bedrock outforms affected the slope of this area, creating high slope angles. This hard forms are not affected by currents or tides, despite of the areas around that are formed for soft clays, due to this fact moat axis have been detected around the bedrocks. Can be observed a low number of fault scarps close to the pockmark structures. On this Figure can be observed a low number of pockmarks that are distributed along all the pipeline path. At the bottom left can be observed an area with a more accurate bathymetric data.

**Figure 19.** Morphological features interpreted. Can be observed bedrock outforms (center), pockmarks (center and top) and moat axis surrounding the bedrock forms.

Figure 20 shows a point where the bathymetric dataset covered and alternative area for the pipeline path. At the end the pipeline followed the left route. This area is comprised between 600 and 650 meters depth, where the most amount of pockmarks and edges have been identified. On this area can be observed both of the most important features identified.

**Figure 20.** Morphological features interpreted. Can be observed pockmarks, and two different Scarps, landslide heads and fault scarps.

Scarps identified have been classified in fault scarps, with a few ones classified as landslide heads. Can be compared the scarp length of both of the different scarps, concluding that fault scarps have a larger length. This fact has been supported by Figure 16. On this figure most of landslide heads have associated a small landslide deposit at the bottom, used as one of the criteria for the identification of this landslide heads. Pockmarks on this area have been detected aligned, and closer to the fault scarps. This alienation it’s the same than the fault scarp edge. This area it’s the start where most of the morphological features are clustered and where they get their maximums of their morphological characteristics.

All this structures are distributed along the pipeline path, supposing an important hazard for the Greenstream. Can be observed how pockmarks and fault scarps use to appear together in the same areas, and pockmarks alignment is strongly related with the fault scarps edges. This relation its more abundant at areas between 600 and 800 meters depth where both of them are clustered.
The qualitative map analysis has been obtained from the interpretation of all the structures founded during the seafloor analysis. This map can be found at the annex 2 (Qualitative hazard map, from the supporting information).

6.2 The Twin slides Area qualitative hazard map

The Twin slides area is one of the most problematic areas for the Greenstream installation. Due to the absence of bathymetric data in this area (not available for the MSc but collected), we have adopted an independent analysis of all the morphological information (Figure 21).

In this map, all of the scarps that have been found have been identified as landslides heads, most of these scarps have been classified as sharp edges. Massive mass-transport landslide deposits, that cover a large portion of the area, can also be identified. The largest of these landslides can be related with the landslide scar at the top of it. It can also be observed that every landslide deposit has a landslide scar at its top, from where the material was originally removed. For the study of the volume of sediment involved on each slide has been calculated from the area of each landslide multiplied for the average height of the fail the section. The northern slide deposit has a calculated area of 58.3 km$^2$, the southern slide has a calculated area of 16 km$^2$. The average height of the failed section that is estimated restoring the regional slope to its prefailure configuration (ca. 100m)(Minisini 2007). Therefore, the combined volume of the two slides is in the order of 7.3 km$^3$. The runouts of Northern and Southern Slides are 11.7 and 10.4 km, respectively (Minisini 2007).

To the west of this area, a sequence of bedforms with a NW-SE direction can be mapped. These bedforms originate from water fluctuations, typical from shallow water depths as it’s suggested for Michalef et al. 2010 about the formation of bedforms.

A small pockmark field can be observed to the SW of Figure 14. The perfect matching of the pockmark field with the slide-related base-of-slope bulge is suggestive of a possible causal relationship.

Figure 21. Interpretation of morphological structures at the twin slides area (Gela basin).
Another morphological feature found on this map has been a field of gullies to the North with a NE-SW trend. These gullies have been identified with the high resolution bathymetric dataset used for this work and cannot be seen on Figure 21.

The other minor structures found in this area are ridges to the South-East and associated moat in the same area.

The area highlighted with (1) is part of the high resolution bathymetric dataset used for this work. This area has been superimposed with the hillshade. This area can be found in annex 2 (Qualitative hazard map, from the supporting information).

6.3 Quantitative analysis

The quantitative analysis at drained conditions revealed a high safety factor along the pipeline path. These maps was created considering that the sediment shear strength is characterized by friction angles of 45º (Figure 22) and 40º (Figure 23) respectively. This friction angles have been extracted from the previous surveys reports.

For the 45º friction angle can be observed a high safety factor along all the pipeline path. Due to the high friction angle used for this map and the low slope angle along the pipeline path (between 0º and 10º) the result has been a high safety factor along the pipeline path. Only a few areas where a strong slope appears reach maximums of 78º, likely at bedrock outforms or at fault scarps edges, the safety factor gets lower, but never arriving to a 0 safety factor value.

For the 40º friction angle the final map doesn’t diverge from the 45º friction angle map. The high friction angle and the low slope factor along the pipeline path revealed a high safety factor value along most of the pipeline path. Again only areas with a strong slope change like fault scarps or bedrock outforms generate the slope to decrease the safety factor.

Both maps reveal a high safety factor along most of the Greenstream route, with a few areas displaying medium and low safety factors. These maps can be found in annex 3 (Safety factor map at drained conditions, from the supporting information).

The quantitative analysis at undrained conditions has been carried out at different depths to handle the complex nature of the undrained shear strength (C) data. For C at 1 meter depth the values obtained, range between 4 kPa and 6 kPa (Figure 24). This value decreases exponentially after this maximum.
Marc Pascual: “The Greenstream: Geological hazards to a submarine pipeline”

For Cu at 2 meters depth, a normal distribution is found where most values are between 4 kPa and 8 kPa (Figure 25).

Finally, for Cu at 5 meters a distribution has been obtained where the majority of measures are between 12 Kpa and 14 Kpa (Figure 26).

Overall, it can be observed that the shear strength value is increased with depth gradually. These values are all contained between a minimum of 0 Kpa still reaching a maximum value of 20 kPa.

The safety factor of these maps became completely different than the safety factor at drained conditions. In this case the resulting saturated soil unit weight has been: $16389.52 \text{ N/m}^3$, it’s a high value that decreases the safety factor due to appear at the denominator of the equation (Equation 3). For this reason most of the values obtained during this analysis appear between 0 and 1 safety factor value.

Three factor of safety maps taking into account the undrained shear strength (C) at 1 meter depth, 2 meter depth and 5 meters depth respectively, have been created.

Figure 27 is affected by multiple geomorphological structures along the area between 600 and 800 meter, this structures affect the slope of this zone, creating a low safety factor. This safety factor gets lower at this points where the slope its mora accentuated than shallow areas, were the Scarps and pockmarks are not clustered. Can be observed an increase of the safety factor at some zones, where the slope its softer and its not altered by other structures. This pattern its repeated along all the pipeline path, and only the shallow areas with slow slopes generate highers safety factors values.
Can be observed a similar distribution compared with the safety factor at Cu 1 meter depth, but in this map the areas with a high safety factor is decreased. Only plane areas at shallow waters present a high safety factor. According to the Equation 3 the increment of the depth (H) value, will increase the denominator result, concluding a lower safety factor.

According to the calculations realized for Cu at 5 meters depth all the pipeline path has a low safety factor value. Indicating that the safety factor decreases with depth. According to the Equation 3 the increment of the depth (H) value, will increase the denominator result, concluding an extremely lower safety factor.

These maps can be found in annex 3 (Safety factor map at undrained conditions, from the supporting information).

7. Discussion

The qualitative geohazard analysis has shown several features that can pose a hazard to the pipeline, particularly pockmarks fault scarps and landslides.

Pockmarks may reactivate and must be considered as a geological hazard that requires special design considerations. (Hovland 1989; Cunningham and Schubert 1980), these authors suggest that pockmarks should be avoided from pipeline routes. During the analysis many pockmarks have been detected (annex 2, qualitative hazard map, from the supporting information) along the pipeline path, especially at depths between 600 and 800 meters (Figure 16D).

All the scarps detected must be considered as well as indicative of potential hazard to the pipeline. Fault scars on the seafloor indicate recent tectonic activity, corroborated by previous studies dating rifting processes during the Neogene - Quaternary (Finetti, 1984). The landslide heads are also an indicator of gravity driven processes, especially those associated with sharp seafloor scarps, indicating a recent event. Like pockmarks most scarps have been identified at depths between 600 and 800 meters (Figure 15).

Figure 18 shows one of these areas where scarps and pockmarks can be found. In this figure pockmarks are often found aligned along the same direction than fault scarps, and really close to them. This situation occurs along most of the pipeline path, especially at depths between 600 and 800 meters. This suggest a strong relation between pockmarks and scarps, i.e. between active tectonics.
and fluid escape to the seafloor. Pockmarks are structures formed because of fluid escape, and these fluids can facilitate the triggering of fault scarp movements and subsequent landslides. Another option is that escaping fluids use the fault planes as a preferential surfaces to escape. But, as said by Hovland et al. (1989), there are still many unanswered questions as to how pockmarks develop.

The Twin slides in the Gela Basin (Figure 15) and any subsequent new failure may create significant hazard to the pipeline. These landslides are clear indication that this area is suitable to mass-transport events (Minisini 2007), besides this fact, previous instrumental and historical studies conclude that since 1970 seven seismic events have been detected in the Twin slides area, indicating significant seismic activity (Minisini 2009). These seismic episodes can be one of the triggers for the reactivation of the landslide system in this area.

The measures calculated at this project for the northern slide deposits are 58.3 km² area and for the southern 16 km², while Minisini at 2007 calculated 5.8 km² and 3.6 km² respectively. This is because as an interpretative analysis the borders of the slides have been projected at different distance than this previous study. The bathymetric dataset at this area is not precise and makes difficult a clear identification of the morphological forms.

All of this structures suppose an important hazard to the pipeline structure. The fault scarps are indicatives of an accentuated slope at this points. A reactivation of this fault scarps can originate an increase of this slope factor. The distance between the top of the fault scarp and the bottom can originate a displacement of the pipeline at some points, this displacement can cause fractures at the structure. The landslide heads are related to landslide episodes, especially the hard slides that indicate a recent movement. A landslide can be one of the causes that can fracture the pipeline structure in two different ways. The first one can be originated if the pipeline is assented on the mass transport zone, this transport can displace the base of the pipeline structure. The second one can occur if the pipeline is in the landslide path, if this happens the amount of material transported can bury the pipeline structure.

Another important hazard it’s the scour, especially in this soft clays where the Greenstream pipeline is placed. This lithology is conditioned by erosional processes, and that phenomenon it’s more accentuated when a hard surface appears, generating moat axis, (Figure 19). As suggests Ghiew, Y at 1990 the scour can be prevented by placing an impermeable membrane underneath the pipeline.

Since pockmarks may be or could become sites of natural gas venting, this gas might suppose an important hazard to the pipeline structure. This fluid scape structures can produce a short term of a gravity based instability, appear under the base of the pipeline path, and long term risk due to growth. For that reason they should be avoided when pipeline routes and platform sites are planned.

If a pockmark cannot be avoided along pipeline routes, implicates a hazard of future eruption because if the local gas accumulations. If it is not 'fresh' and no gas anomalies are found nearby there should be no danger in crossing it. Despite this it’s important to start a monitoring of this structures as soon as possible.

One of the measures to prevent the fluid scape system from pockmarks was proposed for Hovland & Gudmestad (1984), they described a method of seabed drainage of the construction site. This method is based on the assumption that gas below the upper gas-front favors a horizontal bed parallel migration despite a vertical migration. In effect, this means that gas will accumulate below the 'upper gas-front' until it is either prevented from moving laterally or is pumped upwards. This method for artificial seabed gas venting relies on the fact that the upper sediment layer is impermeable to that gas migration and with a cohesive materials saturated. This system consists of penetrating the upper sediment layer with vertically installed drainage tubes. This tubes consist of perforated steel piles which is supported by a baseplate on the seabed. This tubes work as an “artificial pockmark” canalizing the gas migration of the deeper levels through them, and preventing the formation of new pockmarks under the pipeline structure. For that reason this piles must be spaced closely around the construction site to prevent effectively more shallow gas accumulations from forming.

Another important possibility to increase the resistance of the pipeline to different hazards is to work on the pipeline structure. Due to improve the resistance in front of all the geological hazard explained previously it’s important to endow an elasto-plastic behavior. This characteristics must be defined before the construction of the submarine pipeline, due to build it able to resist the tension generated by possible submarine landslides or sudden slope changes. For that reason is
A first approximation to the geological hazard affecting a submarine pipeline has been carried out. A qualitative analysis revealed multiple structures that can pose a risk to the pipeline, especially pockmarks, fault scarps and submarine landslides. This structures have been identified along all the pipeline path, but especially at depths between 600 and 800 meters. This conclude the importance of an geologic hazard study that delimit more precisely which structures could be reactivated and which grade of influence have according to the pipeline characteristics.

A quantitative analysis of the hazard against slope failure revealed that in drained static conditions most of the sea floor along the Greenstream path is stable. The quantitative analysis at undrained conditions revealed the opposite scenario, where all the sea floor along the pipeline route has a small safety factor value. This value only reaches a high value determining stability at plane areas situated at shallow areas free of morphological features like pockmarks or Scarps.

This study provides a first approach to the analysis of submarine hazards to a pipeline, and as such, the results are basically indicative. Therefore, it is important to continue working in the hazard assessment and to continue to improve the tools, in order to get more and more adjusted to the reality of the results.

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Moltes gracies

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8. Conclusion


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