Designing Cost-Effective and Reliable Submarine Communications Cable Path: Lessons From the Tonga Volcano Disaster

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***Abstract*—Submarine communications cables are essential infrastructure in modern society, but they are also vulnerable to unpredictable disasters, and their breakage may have dire social and economic consequences. Motivated by the lessons from the Tonga volcano eruption in 2022, we incorporate the volcano risk factor with the other considerations (including earthquakes, fishing, anchoring, terrain slope, and marine protected areas) that have been considered in previous publications, and explain the Fast Marching Method-based path planning of submarine cables. To consider the effect of volcanos, we also introduce constraints based on keeping safety distances (zero, short or long) from each volcano, by setting infinite risk value in areas to be avoided. We then provide the approximate Pareto front of the cost and risk of submarine cable paths for different stakeholders' reference. We demonstrate that significant cost savings and reduced cable faults could have been achieved for the Tonga-Fiji cable system using our method, keeping in mind that our conclusions are based only on publicly available data.**

***Index Terms*—Submarine cable path planning, volcano, Fast Marching Method, Pareto front, Tonga-Fiji cable.**

I. INTRODUCTION

LONG-HAUL submarine communication cable system using low-loss optical fiber has been expected to play an essential role in international data transmission due to its reliable, economical, and large-capacity characteristics since the 1980s [1]. Nowadays, submarine communications cables (hereinafter referred to as submarine cables) connect the world and carry 99% of the global data traffic [2]. There are 552 submarine cables in use worldwide in early 2023, with a total length of more than 1.40 million kilometers [3]. Almost all countries with coastlines are connected to submarine cables, see Fig. 1. The types of users of submarine cables are extensive. Submarine cables are proving to be catalysts for globalization and international engagement, as they become the cornerstone of globalization and global communications. About 9.1 billion US dollars have been invested in submarine cables during 2017-2021 [2], and about 8.8 billion US dollars are being invested in the construction of new submarine cables during 2021-2023.

Although long-haul submarine cables have been enhanced to provide 224 TB/s optical transmission speed with key advanced technologies [3], submarine cables are still vulnerable to various accidents such as earthquakes, volcanic eruptions, fishing and anchoring, leading to over 100 cable failures per year [3]. Consequently, the repair cost of submarine cables can reach millions of dollars, according to the International Cable Protection Committee (ICPC). Meanwhile, the interruption of submarine cable services may lead to economic losses and social consequences. In 2006, an earthquake of magnitude seven occurred in the Hengchun area of Taiwan, which cut off eight submarine cables, severely disrupted internet services in Asia, and affected many Asian countries where 79% of internet services in mainland China were interrupted [4]. In January 2022, the Hunga Tonga-Hunga Ha'apai volcano erupted, and destroyed a Tonga cable path of around 80 kilometers, causing Tonga to completely lose communication with the outside world for about one month [5]. All of this speaks to the importance of digital connectivity for social resilience and business continuity in times of crisis.

To design cost-effective and reliable submarine cables, the industry currently uses a traditional manual method based on experts' experience. In particular, planners use available data on the target area, from maps, aerial photographs, charts, and satellite gravity bathymetric data, and produce initial alternative paths that connect the starting point to the endpoint with the help of commercial planning software tools, such as MakaiPlan. Then, they conduct a preliminary survey for a given path to verify its feasibility and rationality. Finally, the planners determine the path route after carefully checking all the relevant details along the cable's path and comparing the alternatives thoroughly. This method relies on the subjective judgments of planners. Since a planner cannot always consider all available alternatives given time and resource limitations, this method cannot provide a near-optimal path nor consider various factors that may affect the cost and resilience of submarine cables.

Many publications provide modeling and analysis related to cables and cable networks. Neumayer *et al.* [6] designed a network to mitigate disasters by identifying disaster sites with significant network disruption impacts. Tran and Saito [7] considered the network breakage risk associated with earthquake disasters and planned network links with maximum

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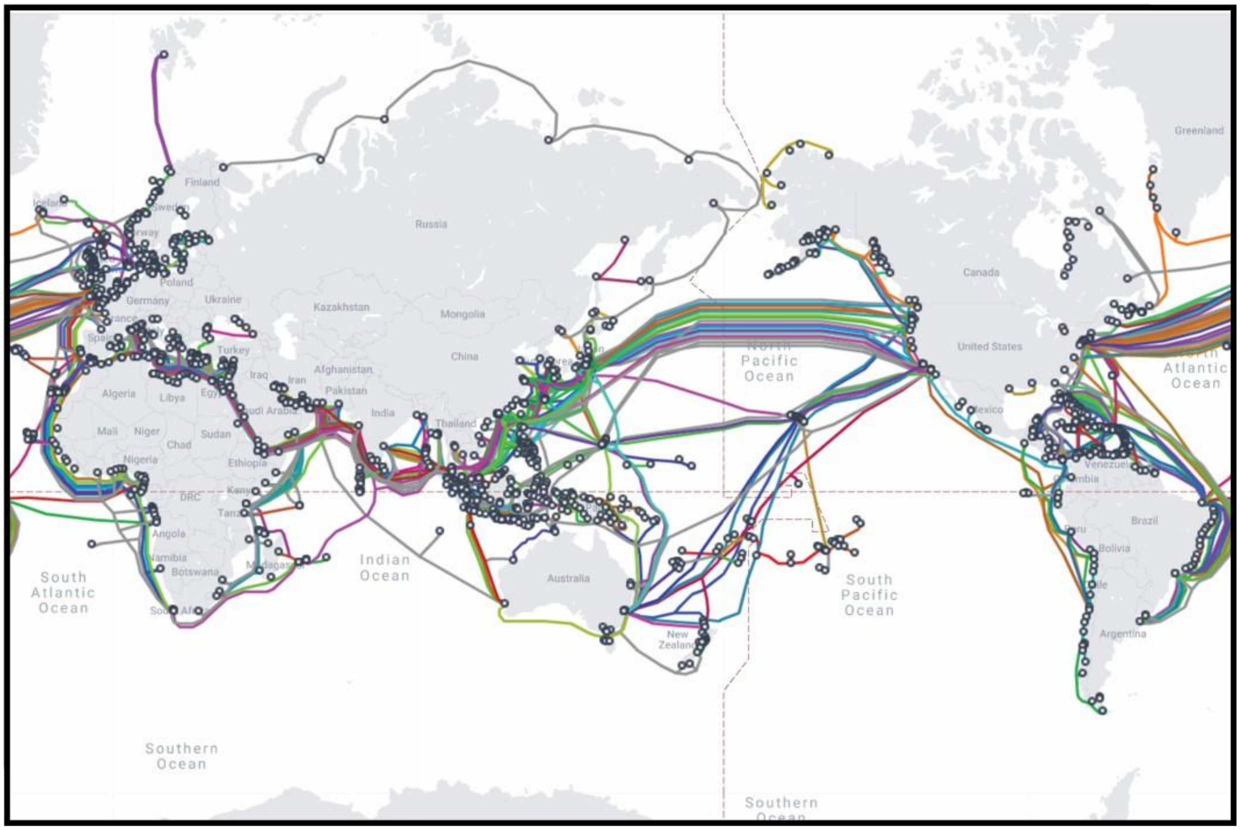


Fig. 1: Submarine cables enable global communications. Source: TeleGeography.

robustness under cost constraints. In [8], Zhao *et al.* used Dijkstra's algorithm, which provided a grid-based path analysis to minimize the cumulative cost along the path. The cost function includes costs related to cable length and earthquake survivability. Blaise *et al.* [9] developed a parallel Dijkstra algorithm to speed up the path design process and considered the curvature constraints of offshore pipeline or cable path planning.

Wang *et al.* [10] considered the more realistic problem of cable path optimization between two given points on the surface of the earth, modeled by a 2D manifold in 3D space, as a multi-objective optimization problem, minimizing a cost function based on a weighted sum of design considerations. Then the problem was reduced to an Eikonal equation and solved by the Fast Marching Method (FMM) [11]. FMM has the benefit that it does not restrict the path to grid points at each step as is the case in Dijkstra's algorithm and achieves an optimal path for a given triangulated manifold. This has been proven in [11]. The superiority of FMM over Dijkstra's algorithm was also demonstrated numerically in [12]. The application of FMM-based optimization approaches to networks of cables was also studied in [12–14]. In [13], multi-resolution and parallel techniques were introduced to speed up FMM and provide higher-quality cable path solutions. In addition to point-to-point cable path optimization, Wang *et al.* [12] extended the work to connect a given point to an existing cable network. The optimization of the cable network was considered in [14].

Motivated by the consequence of the Tonga volcano eruption mentioned above, in this paper, we incorporate the volcano risk with the other considerations that have been discussed in [12] and present a light tutorial on an FMM-based submarine cable path planning method. In addition, by using this method, we estimate the cost associated with cable length and the risk associated with the earthquake, volcanos, fishing, anchoring, terrain slope, and marine protected areas. In the area of the Tonga-Fiji cable, we have a combination of seismic activities and volcanos. While public data on ground motion is available to help us assess potential damage to the Tonga-Fiji cable from seismic activities, accurate assessment of damage from volcanos is more difficult because we only know the location of active volcanos, that is, we do not know accurately from publicly available data the risk level for the cable as a function of the distance from a given volcano location. Given that each volcano may have many eruptions and the intensity of each eruption is measured by Volcanic Explosivity Index (VEI), we consider the highest historical VEI (HVEI) level for each volcano. We use different *safety distances* for different volcanos based on their HVEI levels (the higher the HVEI level, the greater the safety distance). In particular, we choose two alternatives for safety distances for each volcano HVEI level designated as *long* and *short* where the former is the longer of the two and the latter is the shorter. For benchmarking, we also consider the case of no safety distance.

Therefore, we optimize cable path planning under the following three different scenarios:

- Ignoring the effect of volcanos.
- The cable is not allowed to be at any point of its path within a short safety distance of the nearest volcano.
- The cable is not allowed to be at any point of its path within a long safety distance of the nearest volcano.

We compare these three scenarios to assess the cost and risk consequences of introducing these volcano-related constraints. Based on this method, we use Geographic Information System (GIS) software and data from the Asian Development Bank to obtain the longitude, latitude, and elevation of the Tonga-Fiji cable path data and analyze its cost and risk based on publicly available geological hazard data. We use the global elevation data from the General Bathymetric Chart of the Oceans (GEBCO) to obtain the water depth and calculate the terrain slopes. The locations of marine protected areas with seagrass and coral reefs are from the UN Environment Programme World Conservation Monitoring Centre. The historical ground motion data and volcano data are obtained from the United States Geological Survey and the Smithsonian Institution's Global Volcanism Program, respectively.

Considering the historical ground motion data from the United States Geological Survey and the volcano data from the Smithsonian Institution's Global Volcanism Program, we use FMM to design Pareto optimal paths connecting the starting and endpoints of the Tonga-Fiji cable under a terrain slope constraint as well as the above-mentioned volcano constraints. Moreover, we provide approximate Pareto fronts of cost and risk for submarine cable paths for consideration by various stakeholders.

The contributions of this paper are as follows.

1) We apply our FMM-based path planning method on the Earth's surface, cost/risk models, and real geographic data to quantitatively estimate submarine cable cost associated with cable length and risk associated with earthquakes, volcanos, fishing, anchoring, terrain slope, and marine protected areas. Our solutions are optimal given the data, while we only consider publicly available data in this paper. If more data is collected from private sources, the solutions will likely improve as it is again optimal given the data. Limitations of publicly available data include a lack of data for certain design considerations as well as low data resolutions for others. Notice that the above-described publicly available data does not include data for considerations such as sediment hardness and turbulent currents. Also, we use the highest publicly available resolution data from GEBCO, and our solutions can be improved if higher-resolution data can be privately collected.
2) We use GIS software to obtain the real Tonga-Fiji cable path data from [3] and use the method in 1) to obtain the cost and risk values of Tonga-Fiji cable.
3) We provide various alternative Pareto optimal paths for the Tonga-Fiji cable using FMM under the volcano's safety distance constraints and generate approximate Pareto fronts from these Pareto optimal solutions. Note that the volcano safety constraint (along with the other constraints of terrain slope and marine protected areas) is incorporated using an infinite value in the risk objective function. This enables consideration of volcano risk in cable path planning.

The remainder of this paper is organized as follows. In Section II, we introduce the models in submarine cable path planning. Section III introduces how we formulate the problem and implement FMM for submarine cable path planning based on our models. In Section IV, we analyze the cost and risk of the real Tonga-Fiji cable and use FMM to generate Pareto optimal cable paths connecting the starting and endpoints of the Tonga-Fiji cable. Also, the approximate Pareto fronts of cost and risk for each set of safety distance constraints are shown in Section IV. Finally, Section V concludes this paper.

II. MODELS

Here we describe our Earth's surface and cost/risk models that were defined and used in [10, 12].

A. *Earth's surface model*

We use a triangulated two-dimensional manifold model to describe the Earth's surface. In particular, we assign to each point on the manifold a three-dimensional coordinate representing the latitude, longitude, and elevation of this point. See details in [10, 12].

B. *Cost model*

For a submarine cable, we assume that its ***cost*** per unit length at point X is additive and can be written as $c(X)$. It should be noted that $c(X)$ includes the cost of repeaters, which are installed every approximately fixed distance in the range of 45-90 km depending on the cable [15] to help eliminate the signal attenuation. Therefore, for ease of exploration, the total cost is assumed to be linear in the length of submarine cables.

C. *Risk model*

We use the term ***cable repairs*** [10] to represent risk. This is our risk measure in our risk model, and it is not intended to be an accurate estimate for the expected number of repairs. Although for the consideration of earthquake risk, this measure has a relation to the expected number of repairs, for other considerations associated with areas that must be avoided for a variety of reasons, the value of this measure is set to infinity even if it is not related to the expected number of repairs. These areas include, for example, marine protected areas, areas where the slope degrees are larger than 25°, and areas within the volcano safety zone. Specifically, for a given point X on the surface model, we assume its repair rate $r(X)$ to be non-negative and also additive.

We use Peak Ground Velocity (PGV) data to assess the seismic hazard level at a certain point on the manifold. The PGV data is calculated based on historical earthquakes in a region. There is currently no published model that explains the relationship between ground movement and cable repairs. Therefore, we use a known practice of laying water/gas pipelines and apply it to the submarine cable to estimate the expected number of repairs given the ground motion data (namely the PGV data), see more details in [10]. Notice that our estimate may not be very accurate for the expected number of repairs. However, based on experience with water/gas pipelines, it can be used as a relative measure of risk for comparison with other paths.

For cable failure risks associated with human activities such as fishing and anchoring, the breaking probability of submarine cables gradually decreases with the increase in water depth. Specifically, for water depths within 300 meters, from 300 meters to 1000 meters, and over 1000 meters, the average annual number of submarine cable faults caused by fishing activities is 0.069, 0.011, and 0.004 [12], respectively. Also, the average annual number of submarine cable faults caused by anchoring activities within a water depth of 300 meters and over 300 meters are 0.023 and 0.02 [12], respectively. For more details, please refer to [12].

For terrain slope, according to ICPC submarine cables laying guidelines, cables should better be laid in areas where the surface slope is less than 25°. Therefore, as mentioned above, we set the repair rate for the areas with slopes larger than 25° to infinity.

As there are many environmentally sensitive areas on the seabed (e.g., seagrass and coral reef areas) that should be avoided where we set, as mentioned above, the value of the repair rate to infinity.

As mentioned in Introduction, for volcanos, we consider three safety levels. In separate runs, we consider each one of them as a forbidden area by again using an infinite value for the value of the repair rate in the area within the safety zone.

III. PROBLEM FORMULATION AND METHODOLOGY

We aim to design the submarine cable path based on multi-objective optimization minimizing the two objectives ***cost*** and ***risk*** to connect a starting point A and an endpoint B. As mentioned in Section II, the cost $c(X)$ at point X includes cable materials and also repeaters while the risk $r(X)$ at point X is the sum of the repair rates caused by all the factors associated with risk, namely earthquakes, volcanos, fishing, anchoring, terrain slope, and marine protected areas.

To optimize the cost and risk, we transform the multi-objective problem into a single-objective problem through a weighted sum method. Specifically, we use $z(X)$ to represent the weighted cost of point X, which is obtained by the sum of two terms: one is the cost $c(X)$ with coefficient 1, and the other is the risk $r(X)$ with coefficient w. By integrating $z(X)$ from zero to the length of the cable path, we then obtain the optimization objective Z_{AB}, which represents the total weighted cost for the cable path that connects the starting point A and the endpoint B. See more details in [10].

Notice that we only have the data on the grid points for the considerations from the public data sources mentioned in Section I, by using the geometry of the triangulated manifold, we can obtain the value of the objective function for any point on the manifold, not only the grid points. There are no explicit constraints for our objective function, but the cable will avoid areas mentioned in Section II-C where the repair rate is set to an infinite value.

We convert the minimization problem of Z_{AB} to a nonlinear partial differential equation, namely the Eikonal equation. As mentioned in [10], we use FMM to solve it. Specifically, there are mainly two stages in the process of the implementation of FMM in submarine cable path planning. In the first stage, intuitively speaking, a wave is generated at the starting point and propagates outward until reaching the endpoint. As the wave propagates, it touches all the grid points in the manifold, and a value is assigned to each of these grid points that represents the total weighted cost from the starting point to this grid point. This is achieved by setting the propagation speed outward from any grid point to the inverse value of z at that point. In the second stage, we start from the endpoint tracking back to the starting point using the total weighted cost information collected in the first stage. The trackback does not necessarily visit the grid points on the backward path. Let Z^*_{AX} be the minimum total weighted cost between the starting point A and a point X. FMM allows the backtracking path to cross the edges of the triangulated manifold along the steepest descent of Z^*_{AX}. See more details in [12].

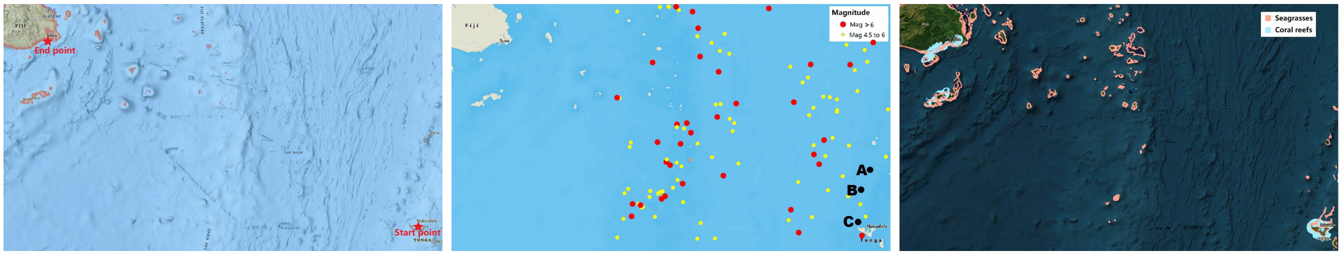
IV. NUMERICAL RESULTS

In this section, we apply our FMM-based method in the Tonga region $\mathbb{D}$ to obtain the cost and risk of the Tonga-Fiji submarine cable and provide alternative Pareto optimal cable path solutions based on different risk-related weights (w). Finally, we derive the approximate Pareto fronts for each of the three volcano safety distance scenarios associated with the cases: no safety distance, short safety distance, and long safety distance.

Fig. 2 shows different maps of Region $\mathbb{D}$. In Fig. 2(b), the historical earthquakes over the last 75 years with a magnitude larger than 4.5 are represented by circles while the volcano locations are represented by letters A, B, and C, respectively. Fig. 2(c) shows the marine protected areas with seagrass and coral reefs.

The Tonga-Fiji submarine cable system connects Tonga with Fiji, starting from Sopu, a suburb of Nuku'alofa in Tonga $(21°08'31.2''\mathrm{S}, 175°13'13.8''\mathrm{W})$ and end with Suva, Fiji $(18°8'43.7''\mathrm{S}, 178°28'53.4''\mathrm{E})$ (see Fig. 3). The elevation data in Fig. 3(a) has been obtained from the GEBCO. The PGV value in Fig. 3(b) has been calculated from the historical earthquake data as shown in Fig. 2(b). Note that a higher PGV value means the more frequent the historical earthquakes.

As mentioned above, our optimization is implemented in three scenarios that are differentiated by the safety distance between the cable and the nearest volcano. Specifically, for the short safety distance scenario, considering the eruption of Volcano A on 15 January 2022 with a VEI level of 5 (highest level in history, namely HVEI = 5) that caused the Tonga-Fiji submarine cable to break [5], which is about 50 kilometers away from volcano A, we set a safety distance of 60 kilometers for volcano A to avoid breaking submarine cable paths. For volcanos B and C, whose HVEI levels are 0 and 1, respectively, we set a safe distance of 1 kilometer for volcano B and 5 kilometers for volcano C. For the long safety distance scenario, we double the safety distances of volcanos

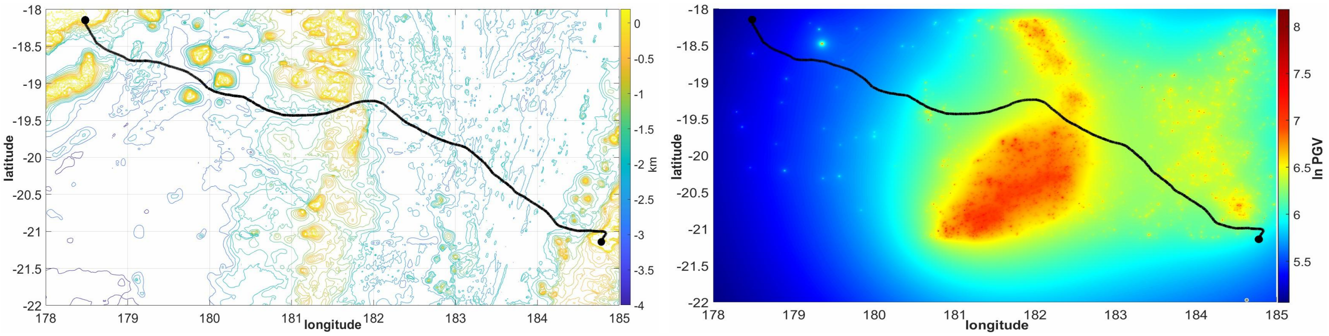


(a) Region $\mathbb{D}$ in Google Earth.

(b) Earthquakes with magnitude larger than 4.5 (represented by red and yellow circles) and volcanos A, B, and C (represented by three small black circles).

(c) Marine protected areas.

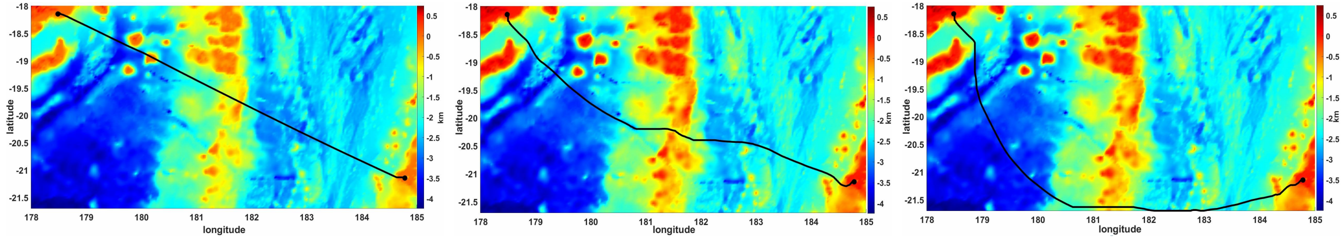
Fig. 2: Maps of region $\mathbb{D}$.



(a) Contour map.

(b) Logarithmic PGV map.

Fig. 3: Tonga-Fiji cable system.



(a) $w = 0$.

(b) $w = 50$.

(c) $w = 100$.

Fig. 4: Three Pareto optimal paths obtained by FMM.

A, B, and C in the short safety distance scenario. For zero safety distance, we set all the safety distances of volcanos A, B, and C to be zero.

By setting $c(X) = 27,000$ USD/km and varying the w value, we can obtain different Pareto optimal cable paths using FMM between the starting and endpoints of the Tonga-Fiji cable. Each of the paths is a Pareto optimal solution for cost and the number of repairs defined in Section II. The results are shown in Table I, where Cable TF is the real Tonga-Fiji cable, and Paths 1-10 are the paths we generated by FMM with the same starting and endpoints of the Tonga-Fiji cable system. Some Pareto optimal Paths are illustrated on elevation maps in Fig. 4.

TABLE I: Results under short safety distance constraints.

	w	Expected number of repairs	Total cost (million \$)
Cable TF	NA	31.2516	22.963
Path 1	0	60.0900	20.441
Path 2	10	46.6327	20.800
Path 3	20	41.1199	21.077
Path 4	30	38.3443	21.207
Path 5	50	37.0688	21.303
Path 6	100	33.1604	21.671
Path 7	150	31.6113	21.819
Path 8	200	30.9397	21.940
Path 9	250	27.7164	22.797
Path 10	300	21.0709	26.448

From the results shown in Table I and Fig. 4, we can clearly see that Paths 1-9 are more cost-effective than Cable TF with lower costs, while Paths 6-10 have better resilience to risk associated with earthquakes, fishing, and anchoring activities compared to Cable TF. Specifically, Path 1 is almost a straight line connecting the starting and endpoints with a minimal cost because $w = 0$, which means only the cost is considered. The trade-off, however, is that Path 1 has to go through earthquake-prone areas with high PGV values and shallow water areas where fishing and anchoring activities very frequently cause cable faults, see Fig. 4(a). As the w's value increases gradually, the path becomes more "tortuous" to avoid earthquake-prone and shallow water areas to reduce the expected number of repairs as much as possible, as seen in Fig. 4, causing an increase in the length which means a higher cost.

It should be noted that the values of the expected number of repairs of each cable path in Table I is the expected number of cable repairs for the cable's entire lifespan (generally around 25 years [3]) of the submarine cable path. Furthermore, considering that various contingent methods can be used to reduce the risk of breakage (i.e., strengthen cable segments in earthquake-prone areas), the actual number of repairs in the lifespan of a certain cable path in Table I may be lower, but as mentioned above, we do not intend to provide an accurate estimate of the number of cable repairs in the future, but to use it as a relative measure of risk for comparison with other paths.

Fig. 5 shows an approximate Pareto front derived from all the Pareto optimal solutions in Table I with blue color and **Safe_Dist_Short** label. We double the safety distances to obtain the approximate Pareto front for the long safety distance scenario. This case is represented by the red colored curve and the **Safe_Dist_Long** label. By setting the safety distances for volcanos with any HVEI to zero, we obtain the approximate Pareto front for the case of the no safety distance scenario. See the green-colored curve with the label **Safe_Dist_Zero**. We use a yellow diamond square in Fig. 5 to represent the cost and number of repairs of Cable TF.

As expected, we see from Fig. 5 that **Safe_Dist_Long** is above **Safe_Dist_Short** and **Safe_Dist_Zero**. Meanwhile, since the three curves are very close, it shows that the constraints of the volcanic safety distances do not significantly increase the cost of the submarine cable, but it protects the submarine cable from breaking due to volcanic activity. Moreover, since the point of Cable TF is above all these three approximate Pareto fronts (see Fig. 5), it implies that the real-life submarine Cable TF is not a Pareto optimal solution. To be specific, given the same cost of Cable TF, namely $C_{(\text{Cable TF})} = 22.963$ million dollars, the number of repairs of **Safe_Dist_Long**, **Safe_Dist_Short**, and **Safe_Dist_Zero** are 28.0131, 27.4957, and 27.0166, reduced by 10.36%, 12.02%, and 13.55% compared to Cable TF, respectively. Likewise, if submarine cable paths with the same number of repairs as Cable TF are acceptable, namely $R_{(\text{Cable TF})} = 31.2516$, **Safe_Dist_Long**, **Safe_Dist_Short**, and **Safe_Dist_Zero** provide more cost-effective cable paths with costs of 22.1176, 21.9503, and 21.8251 million dollars, saving 3.68%, 4.41%, and 4.96% of the cost compared to Cable TF, respectively.

However, we must keep in mind that our solutions are based only on publicly available data, which may not include other data that was available to the designers of the real Cable TF.

V. Conclusion

Motivated by the lessons from the Tonga volcano disaster, we have incorporated the volcano risk consideration together with the other considerations considered in previous publications for submarine cable path planning. In addition, we have explained how to apply our FMM-based method on the Earth's surface model and cost/risk models for cost-effective and reliable submarine cable path planning. We have also assessed the cost and risk (based on the number of repairs) of the existing real Tong-Fiji cable and provided alternative Pareto optimal paths for cost and risk leading to several approximate Pareto fronts, each for a different volcano safety distance constraint. We have demonstrated that significant cost savings and risk reduction could have been achieved using our automatic path planning methodology, meaning that our FMM-based method described in this paper can provide the best cable paths given the data. However, we must make it clear that our automatic solution cannot completely replace the current manual method based on collecting detailed data in areas close to a path by surveyors and using it in the path planning process. Our solutions have the limitation that they are only based on publicly available data, so they can only serve as a reference for comparison and benchmarking for cable path planners and surveyors to consider in their path-planning process. In addition, our automatic solutions can be further enhanced by using data collected by surveyors to complement the publicly available data.

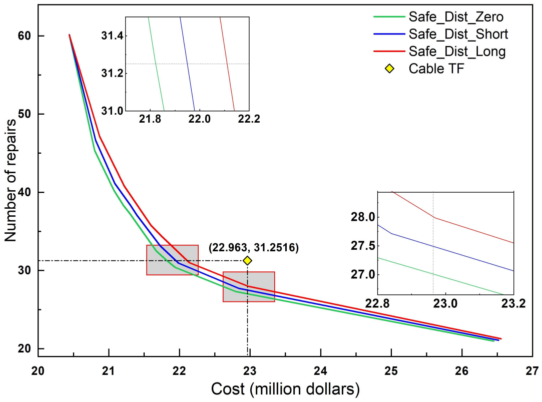


Fig. 5: Approximate Pareto fronts for different safety distances.

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