Bioturbation, Erosion, and Seismic Activity Make Shallow Soil Covers Ineffective at Isolating Contamination

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More than a decade ago, the Navy shifted its remedial approach at the radioactive and chemically contaminated Superfund site Hunters Point Shipyard (HPS) from removal of contaminated soil to leaving it beneath a cover of two (or in some cases, three) feet of "clean" soil or four inches of asphalt across large portions of the site. The stated purpose of the soil cover is to prevent exposure of contaminants to future residents and users of the site. However, there is strong evidence that suggests thin soil covers are incapable of withstanding certain processes such as bioturbation, erosion, and seismic activity which, over time, could potentially compromise their efficacy and durability. The following paper reviews some of the challenges posed by these geotechnical and biological processes which may impact the effectiveness of a soil cover.

The inadequacy of soil covers has been previously recognized by governmental bodies. In 2013, for example, the state of New York issued guidelines[1] for isolation of soils contaminated with radioactive materials, stating that the use of a clean soil cover "may be acceptable for *short-lived isotopes* assuming that restrictions to land use are used until the radionuclides no longer pose a threat" (emphasis added). This position is based on the recognition that soil is not a stable cover that can be assumed to offer long-term protection from exposure to the contaminants beneath it. The rationale behind the New York guidelines would presumably rule out the remedial plan for HPS where contaminated soils contain many long-lived radionuclides and persistent toxic chemicals.

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The cover design being used at HPS is a simple, shallow soil cover, susceptible to failure from various processes. Further analysis below will provide explanation of key mechanisms which prevent a shallow soil cover from being a suitable permanent remedy for the contamination at HPS.[2]

Biological and geotechnical issues that threaten the integrity of a soil cover are:

1. Bioturbation and subsequent transfer of contaminants through the cover by burrowing mammals, insects, and vegetation
2. Erosion by runoff of rainfall, e.g. from the centrally located northwest-trending bedrock ridge
3. Strong seismic ground shaking and liquefaction

Potential Effects of Biointruders on the Soil Cover

As Gabet et al. note in "The Effects of Bioturbation on Soil Processes and Sediment Transport"[3]:

> Although we are most familiar with the animate world that lives above ground, many plants and animals are substantially invested in obtaining resources (e.g., nutrients, water, and mates) in the soil or seeking the protection of the soil from predators, consumers, or environmental variability. To do so, they must penetrate the soil vertically and horizontally. Consequently, they can have strong direct influences on the soil as they generate spaces by excavation or pushing soil aside.

This is problematic for contaminated sites where hazardous and/or radioactive materials are kept beneath a layer of topsoil. In the case of Hunters Point Shipyard, the waste barrier is particularly vulnerable due to a combination of two major factors; (a) the recorded presence of biointruders at and around HPS, and (b) the shallow depth of the planned soil cover.

Numerous studies have identified the activities of burrowing animals as a significant problem at waste burial sites, where they can inadvertently facilitate the migration of toxic wastes. As stated in Smallwood, "Animal Burrowing Attributes

Affecting Hazardous Waste Management"[4]: "Animal burrowing has been generally associated with upward movement of radionuclides at Hanford. Soil bioturbation is the most likely explanation for the frequent and widespread discovery of radiological contamination on surface soils continuing to this day [citations omitted.]" They note that of 101 buried waste sites, "87% were identified as having problems. Twenty-one of these sites were rated as having a history of spreading contamination, 18 showed evidence of biouptake or contamination beginning to 'move around,' [and] 28 were rated as having a 20% - 50% chance of migration or uptake by plants or animals."[5]

Similarly, a study by Bowerman and Redente concluded that "large burrowing mammals (such as prairie dogs), deep-rooted plants (e.g., trees and shrubs), and harvester ants are the greatest risk to barrier integrity."[6] The Smallwood study concurs, stating that "soil bioturbation has been given relatively little consideration, despite the likely variety and magnitude of impacts on waste management systems."[7] They say further, "Soil bioturbation can also degrade the integrity of intentionally buried waste storage systems, exposing hazardous materials to fossorial animals, their predatory and commensal associates, and downwind animals including humans [internal citation omitted]." [8] Further, in a review of the Sandia National Laboratory's mixed-waste landfill site in New Mexico, former Los Alamos National Laboratory environmental scientist Tom Hakonson, Ph.D., states "Burrowing by animals and insects also has the potential to access buried waste several meters below the ground surface. This can lead not only to chemical and radiation exposures to the organisms but also to physical transport of the waste upward in the soil profile to ground surface."[9]

Evidence of burrowers having disturbed a soil waste barrier has been documented at a number of other contaminated sites, including the Hanford Nuclear Reservation, Rocky Flats Plant, Los Alamos National Laboratory, and the Idaho National Engineering Laboratory.[10] For example, Smallwood reported that the "impact of soil bioturbation was grossly underestimated and undermitigated for buried and surface-deposited radionuclides and nonvolatile chemicals and metals at Hanford Nuclear Reservation and Rocky Flats Plant, where animal burrowing continues to excavate and spread the wastes."[11] A study referenced by Smallwood found that the activity of burrowers and depth of the soil cover have a direct relationship to the radioactive dose rates of certain burrower species at the Idaho National Engineering Laboratory.[12]

Moreover, at the Berkeley Landfill in Alameda County, CA, rodent populations have had significant impacts on the landfill soil cover. As stated in a document by the San Francisco Bay Regional Water Quality Control Board, "Burrowing animals present a threat to the water quality at the landfill because they dig tunnels into, and possibly through the landfill cover."[13] This tunneling erodes the land and can eventually lead to the leaching of toxins into the groundwater and the Bay as surface water comes into contact with the waste mass via these intrusive tunnels.[14]

Furthermore, upon reviewing a number of different barrier types, the principal finding of Bowerman and Redente is that "biointrusion is a process that can occur, and that it can become a problem at burial sites regardless of the sophistication of the barrier design."[15] Some of the waste barrier designs that were surveyed in their study were much greater in thickness than the HPS cover, and consisted of multiple layers of varied materials such as gravel, clay, sand, and stone.[16] Considering that the soil cover at HPS is merely two (or sometimes three) feet thick, it is of concern that biointrusive processes have infiltrated these far more sophisticated barrier designs. A study referenced earlier by Hakonson about a proposed cap at a Sandia National Laboratories site states that an addition of "less than two meters of clean soil during ET cap [an evapotranspiration cap, i.e. vegetated soil] construction does not assure that problems with biointrusion go away. Most plants and many animals have the potential to penetrate deeper than the proposed thickness of the ET cover."[17] A soil cover of just a couple of feet is simply not an effective method for protecting human health and the environment at Hunters Point.

San Francisco Bay Area Biointruders

The San Francisco Bay Area is home to a number of burrowing mammal and insect species,[18] some of which have been shown to significantly alter their surrounding environment, specifically by their ability to move great quantities of soil.[19, 20, 21, 22]

Burrowing Mammals In the San Francisco Bay Area

The following table lists burrowing mammals local to the San Francisco Bay Area[23] that are known to produce extensive and geologically disruptive burrow networks.

Table 1. Burrowing Depths of Mammal Species Local to SF Bay Area

Species	Max. Burrowing Depth (ft)
Botta's Pocket Gopher (*Thomomys bottae*)[24]	6
California Ground Squirrel (*Spermophilus beecheyi*)[25]	5.5
Herrmann's Kangaroo Rat (*Dipodomys heermanni*)[26]	2.5
California Vole (*Microtus californicus*)[27]	0.5
Broad-footed Mole (*Scapanus latimanus*)[28]	>1
Norway Rat (*Rattus norvegicus*)[29]	4.9
Mountain Beaver (*Aplodontia rufa*)[30]	5.9

Of the seven species listed above, four have been found to create burrow networks at depths far beyond the two or three foot soil cover proposed at HPS. The creation of burrows in and beneath the soil cover compromises the structure of the soil, facilitating other physical processes such as erosion and bioturbation by vegetation. As stated by Smallwood, gopher burrowing "creates void space, which allows water and plant roots to infiltrate to greater depths more quickly, serves to aerate soils, and serves as habitat for many fossorial animal species that did not create the burrow."[31] Burrowing mammals are constantly producing new burrow networks, which over time have significant impact on the soil.[32] According to a study on bioturbation and its impact on geomorphological processes, "Gopher excavation also accelerates physical processes, such as downslope soil movement, movement of water, and even gully formation to the extent that the magnitude of the effects constitute a major factor in soil movement."[33] Moreover, there are two studies—one which analyzed the amount of soil disturbance exerted by gophers in Alpine environments,[34] and one which looked at flux rates in Marin County[35]—which have found that pocket gophers, a bioturbator local to the SF Bay Region, were the primary mechanism of sediment transport. All of this burrowing activity can result in the transport of contamination located beneath the soil cover to the soil surface, as a result of the excavation of subsurface soils into consolidated mounds. Those mounds can contain contaminated soil when burrowing networks are deep enough to penetrate the soil cover; this contamination is then subject to dispersal via migration pathways such as wind, water, and biota.

The potential for soil barriers to be penetrated by burrowing mammals has already been recorded in areas of HPS. In the Navy's Third Five-Year Review of Remedial Actions (2013), there is documented evidence of animals burrowing into the soil cover installed at IR-07/18.[36] The construction of the cover was completed in September of 2011,[37] and evidence of disturbance by burrowing animals was reported in 2013 Five Year Review, indicating that biointrusion occurred fairly rapidly following its construction—extremely rapidly, considering the length of time the soil cover must remain protective (until all contaminants have been rendered inert). Figures 1 and 2 depict the burrowing animal activity at HPS as recorded in 2013. The next year, following attempts to repair the damage caused to the cover by the initial burrows, the Navy's Annual Operation and Maintenance Summary Report for Installation Restoration Sites 07 and 18 (2014) documented evidence of new burrowing activity in the soil cover during both the First and Second Semiannual Inspection.[38] Finally, in 2018 animal burrows were again documented at IR-07/18.[39]

Further confirmation of the presence of burrowing mammals at HPS is given in a 2009 Biological Resources Technical Report for the SF Redevelopment Agency (now OCII) and the SF Planning Department. The report claims the "most abundant mammal observed during the Yosemite Slough Watershed Wildlife Survey was the California ground squirrel (Spermophilus beecheyi)….Other mammals observed during the survey included…Botta's pocket gopher (Thomomys bottae), California vole (Microtus californicus), and Norway rat (Rattus norvegicus)."[40] The Yosemite Slough Watershed

Wildlife Survey Study Area is situated on and near HPS: "…bordered by Thomas Avenue, Ingalls Street, Carroll Avenue, Fitch Street, Arelious Walker Drive, and the Hunters Point Expressway."[41] Figure 3 illustrates the location of the study area, which runs along Parcel E and E-2 which are large areas where the contamination is proposed to be covered with soil. In fact, the Navy stated in the Phase 1A Ecological Risk Assessment Volume 3, Task 5 Summary Report that, "Evidence of a burrowing animal, probably a mammal, has been seen in nearly every portion of Parcel E."[42] Finally, the Navy has demonstrated their understanding of the potential long term implications resulting from biointrusion through contaminated soils. In the ecological risk assessment they state, "Many organisms present at HPA [HPS] either feed on decaying organic material in soil or burrow through soil. This pathway represents the entrance of soil contamination into the terrestrial food web as organisms such as earthworms, Botta's pocket gopher (Thomomys bottae), and California meadow vole (Microtus californicus) burrow through the soil. When these organisms are preyed upon, they possibly pass these contaminants up the food chain."[43] There exists substantial evidence which corroborates the presence of burrowers at HPS and moreover the soil cover's likelihood of continued disruption by those animals.

Burrowing Ants

It is common for a number of insect species, particularly ants, to excavate soil from depths far greater than the HPS soil cover, and to physically transport soil to the surface.[44] Harvester ants, several species of which are found in the SF Bay Area, have been shown to "burrow to depths of 1 to 4 m and concentrate radioactive waste in their mounds when located at or near sites with contaminated soil."[45] This is especially troubling when considering the apparent affinity of harvester ants for "disturbed areas that are often associated with areas of waste burial," demonstrated by their documented abundance at a number of waste burial sites across North America including the Hanford 300 Area and Idaho National Engineering Laboratory.[46] Harvester ants can be powerfully destructive in these locations as they have been proven to be capable of penetrating through a multitude of barrier types.[47] Further, there exists an abundance of other ant species in California, many of which create pervasive burrowing nests in which they excavate soil from great depths up to the soil surface. Table 2 records some of the ant species native to California that can generate burrow networks far deeper than two feet. The maximum depths of the ant burrows are substantial, at times reaching more than six times the depth of the proposed soil cover for HPS.

Table 2. Burrowing Depths of Ants Native to California

Species	Max. Burrowing Depth (ft)
Pogonomyrmex californicus[48]	6.6
Pogonomyrmex occidentalis [49]	>9.8
Pogonomyrmex owyheei[50]	8.9
Pogonomyrmex rugosus[51]	13.1
Pogonomyrmex salinus [52]	7.6
Pogonomyrmex subnitidus[53]	13.1
Prenolepis imparis[54]	11.8

Ant species have been found to not only penetrate soil to great depths, but to move significant volumes of soil. A Department of Energy (DOE) study which analyzed the major ecological pathways of radionuclide transport at the Hanford Site 300 Area declared, “Clearly, harvester ants possess the potential for moving small particles of contaminated material to the surface where it could be further distributed by wind and by biota.” Further, DOE stated that the only means to deter ants from permeating the soil cover was through chemical control, though even this was found to be largely ineffective.[55] Indeed, the potential for ant species to cause destruction to soil barriers should not be ignored.

Plant Root Intrusion, Uptake, and Transfer of Contaminants

As indicated in the companion paper by Dr. Bianchi, root systems of vegetation—both edible and non-edible—have been shown to penetrate far past the thin soil cover depth employed at HPS and to provide pathways for upward migration of contaminants. Therefore, that topic, an important aspect of bioturbation, will only be briefly touched upon here.

Bowerman and Redente concluded that plant root intrusion was a significant challenge for waste barriers surveyed in their study.[56] The two main impacts of root intrusion that are likely to occur, according to their findings, are "(i) transport and dispersion of wastes out of a disposal site and (ii) physical damage to a barrier."[57] Trees, landscaping, and other plants can serve as a pathway where contaminants in the soil are drawn upwards through their root systems and into the plant body, where they will then accumulate throughout the plant. Bowerman and Redente's research further concluded that evidence of absorption of radionuclides by plants had been recorded at a number of buried waste sites including at the Idaho National Engineering Laboratory, Los Alamos National Laboratory (New Mexico), Hanford Site (Washington), Maxey Flats (Kentucky), West Valley (New York) and Oak Ridge (Tennessee).[58] Once accumulated, the contaminants can be reintroduced into the environment through decomposition of the plant leaves, seeds, and branches, or through more extreme pathways such as the fires that recently devastated much of California. Indeed, Gabet states in no uncertain terms that "Bioturbation has important consequences in the natural processes of all ecosystems as plants and animals penetrate and mix soil. Although these effects are characteristic of ecological systems, they can cause significant disruptions in the burial of hazardous wastes where the intention is to maintain a set of conditions below ground. When wastes are buried, the goal is that the material not be mixed in with the soil (and particularly not be brought to the surface) and that the waste material not seep into the water table. As shown, mixing and increases in infiltration capacity are two of the most common results of bioturbation."[59]

Seismic Conditions and Erosion

Seismic conditions at HPS increase the vulnerability of the waste which lies beneath the soil cover. Lying between two major active faults, the San Andreas and the Hayward (Figure 4), Hunters Point is at risk of intense seismic shaking that can cause severe damage from liquefaction in large parts of the site (Figure 5) as well as structural damage to buildings and infrastructure. In the case of a seismic event, intense shaking and possible liquefaction could very well expose contaminated soils beneath the thin soil cover.

Moreover, there are a number of environmental conditions present at HPS that pose threats to the use of waste capping or covering methods. The Center for Public Environmental Oversight warns that localities experiencing "high rates of subsidence" and "regions prone to earthquakes" should be especially vigilant when using soil caps, as "changes in conditions, such as soil moisture and earth movement...[are] indicators of potential problems."[60] Additionally, they warn that "fluctuations in air temperature and precipitation may also affect the cap's integrity by causing cracking or erosion."[61]

Erosion has been recognized as a considerable hurdle for waste barrier systems. An EPA document titled "Draft Technical Guidance For RCRA/CERCLA Final Covers" concludes, "Excessive erosion of the surface layer has been a significant problem for a number of cover systems. Gullies extending to a depth of 100 to 200 mm are not unusual."[62] The document references a study of twenty-four landfill cover systems in the United States and concludes that "33% had slight erosion, 40% had moderate erosion, and more than 20% had severe erosion."[63] Moreover, erosion by runoff from relatively impervious rock exposures takes place as sheet flow and concentrated flow in rills and gullies. In the past, erosion has significantly modified the land surface at Hunters Point, which consists in some places of substantial fill, creating deep gullies that render those areas particularly vulnerable to ground shaking and liquefaction. Construction of buildings on capped surfaces will protect soil beneath them from erosion by runoff, but, unless carefully controlled, the resulting concentration of runoff between buildings will enhance erosion.

Conclusions

This paper discusses some of the natural mechanisms whereby a shallow soil cover's integrity can readily be breached. There are multiple lines of evidence which suggest that a soil cover of two or three feet is insufficient in barring the movement of contaminated soils by mechanisms such as biointrusion by burrowing animals and vegetation, and erosion and seismic activity. There is strong evidence that burrowing animals known to inhabit the San Francisco region are capable of creating burrow networks at depths far beyond the proposed cover at HPS. These burrowing animals not only modify the structure of the cover, but in generating their burrow networks, are capable of excavating significant amounts of contaminated soil to the soil surface. Further, the literature cites instances where even a highly sophisticated cover design cannot prevent the disruption of soils just two or three feet beneath the surface. Finally, even if the soil cover's integrity were to be maintained and unaffected by such geotechnical processes, there are additional biological mechanisms, described in more detail in the companion Bianchi paper, that enable the migration of contamination deep within the soil to the surface. The soil covers to be employed at HPS are far less substantial than necessary, considering the aforementioned conditions and risks. Therefore, the proposed cleanup remedy at HPS, to leave chemical and radioactive contaminated soils beneath a thin cover of clean soil, should be reconsidered in recognition of the ineffectiveness of that remedy.

Figure 1. Deep Burrow Documented at IR Site 07/18[64]

Figure 2. Multiple Burrows Documented at IR Site 07/18[65]

Figure 3. Map of the Yosemite Slough Watershed Wildlife Survey Study Area[66]

HT Harvey, 2009; LSA Associates, 2004.

PBS&J 10.27.09

Figure 4. Map of Major Faults in San Francisco Bay Area[67]

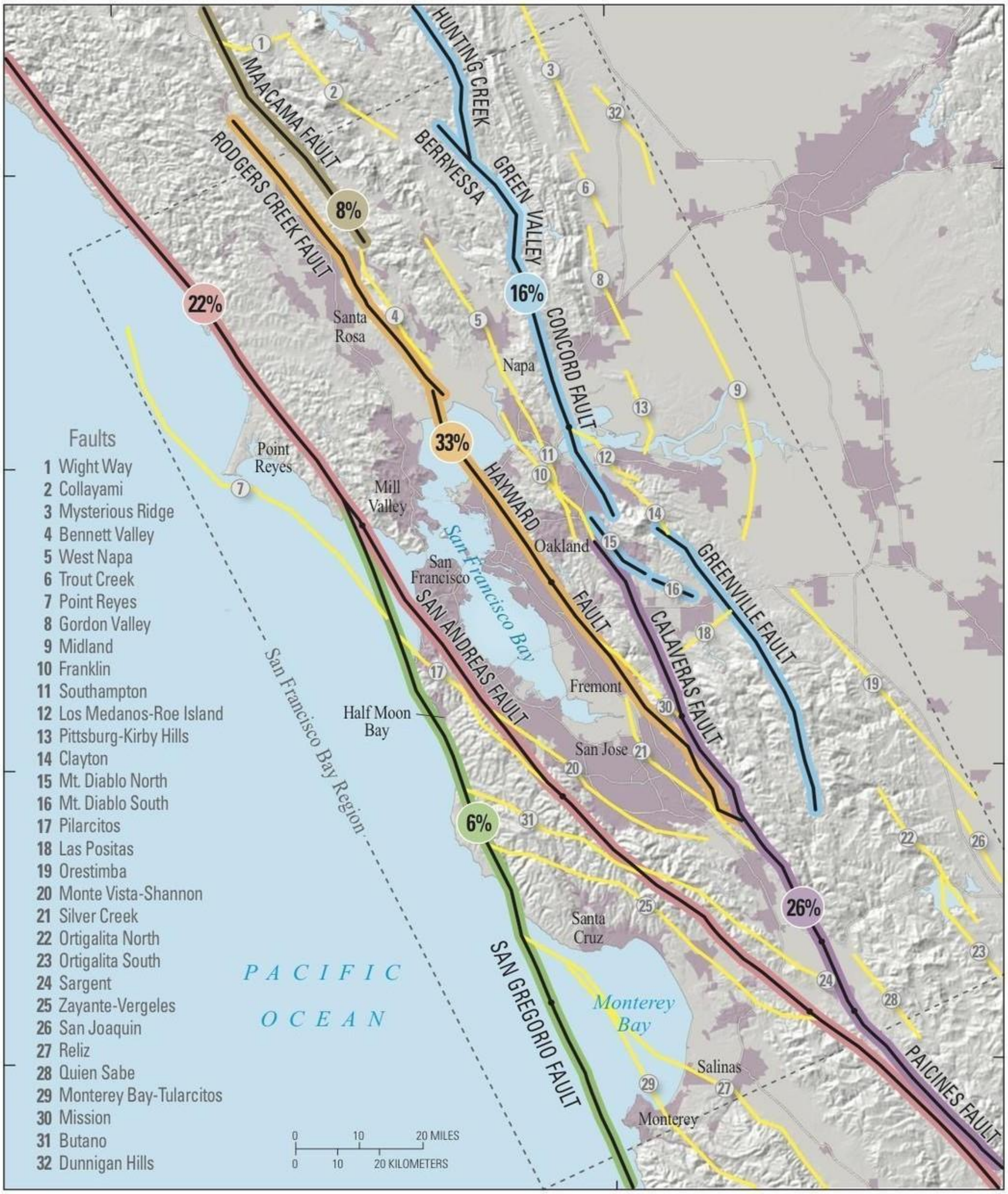
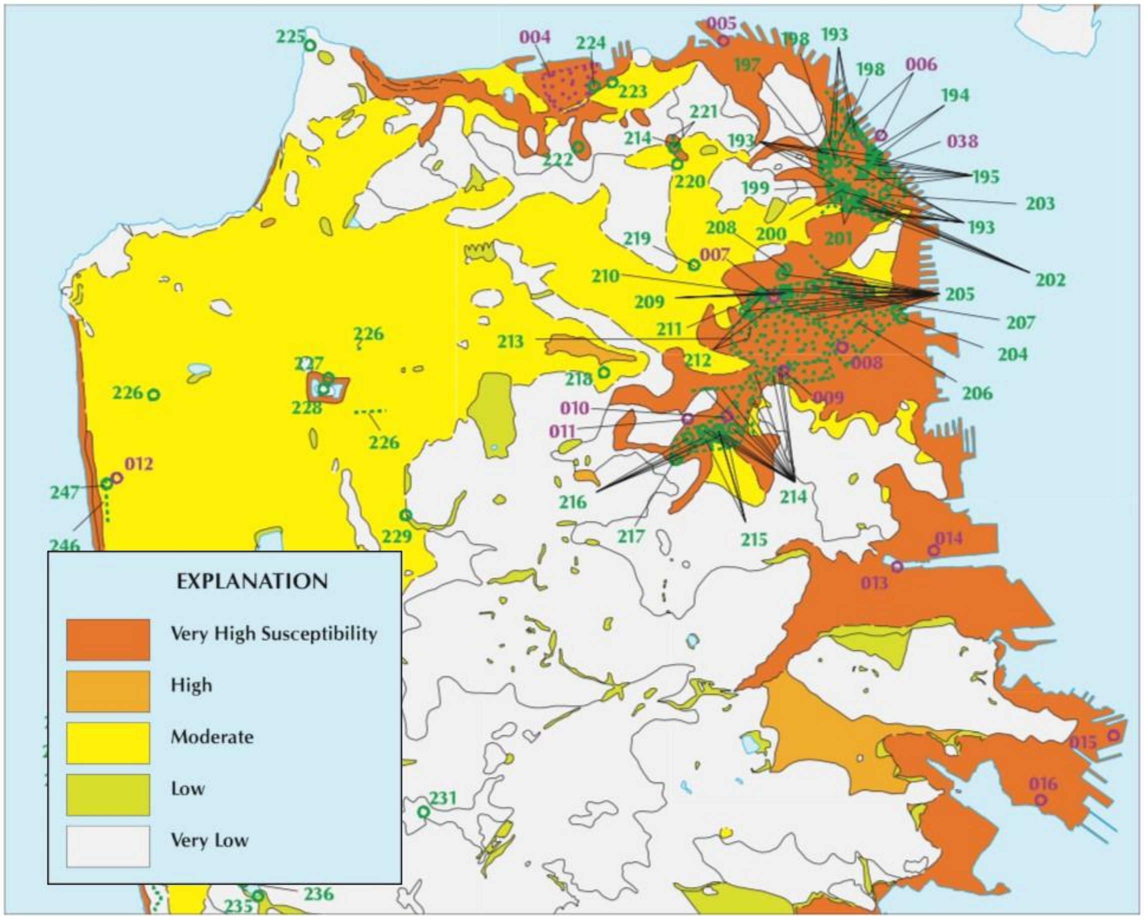


Figure 5. Map of Intense Liquefaction Risk at Hunters Point Shipyard[68]



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