SIMULATED GAS HYDRATE DECOMPOSITION ON AN INFINITE SLOPE

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ABSTRACT

In recent years gas hydrates have become of great interest as a potential energy source, a factor in global climate change and as a significant geohazard. The last of these interests has been deemed to be of immediate importance for safe production of hydrocarbon reserves. When gas hydrate is exposed to changes in pressure and/or temperature, beyond the stability zone, the compound dissociates and results in the release of a large volume of gas and fresh water into the previously cemented sediment. Several case studies of submarine slope failures were reviewed to determine the role of gas hydrate dissociation on the initiation and propagation of the slides. A numerical program investigating the effects of hydrate decomposition on the stability of a simulated infinite slope was undertaken. This paper illustrates that the dissociation of even small percentage of gas hydrates has an adverse effect on the stability of submarine slopes.

RÉSUMÉ

Dans les années récents les hydrates du gaz ont devient de beaucoup de intérêt comme un source potential de l'énergie, un facteur en le changement global de climat et un geohazard significatif. Le dernier de ces intérêts a été estimé d'être d'importance immédiat pour la production sûre des réserves d'hydrocarbure. Quand l'hydrate de gaz est exposé à les changes de pression et/ou de la température, au delà de la zone de stabilité, le composé dissocie et résulte en le relâchement d'un grand volume de gaz et d'eau fraîche dans le sédiment précédemment cimenté. Ce papier illustre que la dissociation des hydrates de gaz à un effet négatif sur la stabilité des pentes sous-marines. Plusieurs études des échecs de pente sous-marine sont réexaminé pour déterminer le rôle de la dissociation des hydrates de gaz sur l'initiation et la propagation des échecs. Un programme numérique examinant les effets de la décomposition d'hydrate sur la stabilité d'une pente infini simulée a été entreprise.

1. INTRODUCTION

Gas hydrates are unique compound of gas, most commonly methane, which are trapped within an ice lattice. The specific temperature and pressure requirements necessary for the formation of gas hydrate exist in permafrost and offshore conditions around the world. The majority of gas hydrates exist in coastal regions, where they are found both on the seabed and more commonly cemented with the seabed sediments.

Little is known about the geomechanical behaviour of gas hydrates and how their presence effects the behaviour of the surrounding soil. It has been found that the solid form of gas hydrate increases the strength of the sediment making their existence no concern for slope stability. However, when these gas hydrates dissociate due to changes in the pressure or temperature the release of the contained gas causes a reduction in strength and a weakening of the sediment and the soil structure. The resulting gas filled soil structure is significantly more prone to instability.

There are three major issues that gas hydrates raise: (1) the use of gas hydrates as a potential energy resource, (2) the role of gas hydrates in global climate change, and (3) the role of gas hydrates in submarine slope stability. The last of these has been deemed the most immediate concern, as with increased development and exploration of the coastal regions there is greater potential for human-hydrate interaction and the potential adverse effects on slope stability.

2. HYDRATE STABILITY

Gas hydrates are stable under low temperatures and high pressures; these conditions typically exist under terrestrial permafrost regions and offshore in the vicinity of the continental margins.

The hydrate stability zone in a marine environment is a function of the water depth and the geothermal gradient. Gas hydrates are generally not stable at water depths less than 150m and seafloor temperature greater than 0 degrees Celsius (See Figure 1). Gas hydrates can exist along any coastal margin given these pressure/temperature conditions as long as there is an adequate source of methane.

2.1 Mechanisms of Dissociation

Mechanisms of gas hydrate dissociation may be of natural or anthropogenic sources. Natural sources stem from changes in the environment while man-made mechanisms generally cause hydrate dissociation within the vicinity of the project.

Two natural mechanisms for initiating gas hydrate dissociation are a sea level decrease and/or sediment temperature increase. A lowered sea level reduces the

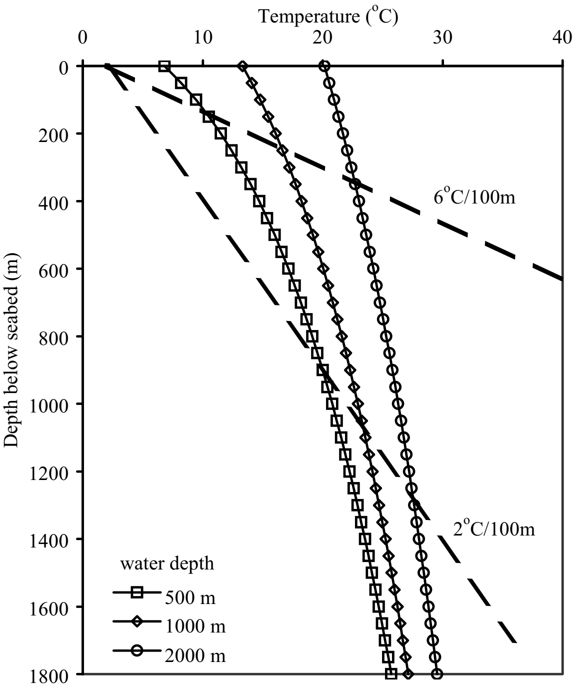

Figure 1. Gas hydrate stability diagram (based on equation by Kamath et al. 1987) for two geothermal gradients and three water depths (Grozic and Kvalstad 2001).

total stress acting upon seafloor slopes and part of the gas hydrate is driven out of the stability range. Environmental changes that alter either the geothermal gradient in the soil or the water temperature above the seafloor could impact the location of the hydrate stability zone. These two natural mechanisms are considered the main factors for large-scale dissociation, as they will affect the hydrate stability over large areas. Therefore, extensive dissociation of hydrate within the sediment could result in large masses of sediment losing strength. Other smaller scale mechanisms can be local slumping, erosion, and sedimentation.

There are man-made mechanisms that could result in local, or small-scale, dissociation that may be detrimental to engineering projects in the immediate vicinity. For instance gas hydrate dissociation in oceanic sediments, caused by temperature increases during petroleum production from a hot oil conductor can melt the hydrates that are in the vicinity of the foundations piles which can result in the failure of the structure (Chaouch and Briaud 1997). Yakushev and Collett (1992) described drilling and production problems because of gas hydrates, which included uncontrolled gas releases during drilling, collapsed casings and gas leakage to the surface. When drilling penetrates a gas hydrate the drilling mud becomes highly gasified as the hydrate dissociates due to the heat of drilling causing casing collapse, gas leakage outside of the conductor casing, and gas blowouts. Therefore it can be seen that local disturbances that push hydrates beyond the stability zone can cause sufficient dissociation to be harmful to development projects. These projects may not be concerned with the hydrates directly but their presence in the area will affect design and implementation.

3. SLOPE STABILITY AND GAS HYDRATES

Gas hydrates are suspected to have caused submarine slides and slumps around the world's continental margins. Theoretical analyses have shown that dissociation of gas hydrates will produce highly gas charged sediments with no cementation, high pore pressures, and low strengths. If the dissociation process occurs to a sufficient extent and over a large enough area, slope failures will result (See Figure 2).

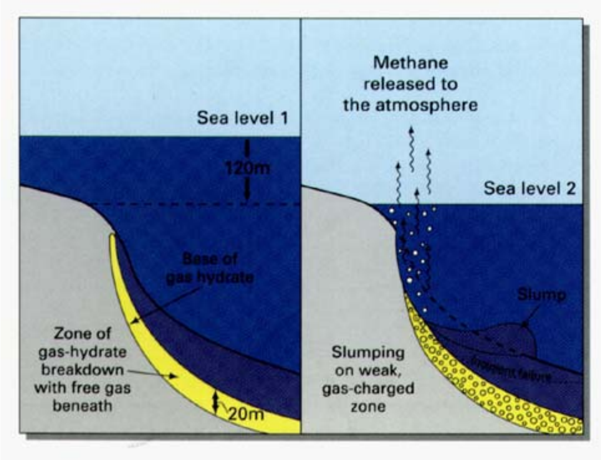

Figure 2. Diagram of effects of gas hydrate dissociation (www.pubs.usgs.gov/ fs/gas-hydrates/).

For decomposing gas hydrates to be a widespread cause of slope failure, three criteria must be met (Dillon et al. 2003): (1) gas hydrates must not only be present, but must be widespread as well; (2) slides must have originated in areas that are within the gas hydrate phase boundaries; and (3) sediments of low permeability must be common at the base of the hydrate zones (to permit the build up of excess pore pressure that could lead to unstable slopes during sea-level falls). In attempt to show a connection between the presence of gas hydrates and submarine slope failure certain case studies have been investigated and their causes of failure analyzed. Each of these cases has been shown to meet the three criteria needed for slope failure.

3.1 The Storrega Slide

Off the western coast of Norway in the Norwegian Sea there occurred one of the largest known landslides in recent history. The slide took place on the Norwegian continental slope extending out into the Norwegian Basin, during three slide events. The enormous volume of material, estimated to be about 5580 km^3, caused a tsunami to strike the East coast of Scotland and parts of Britain.

The Storegga Slide occurred in three separate slide events. The first slide occurred 30000-35000 years ago. The second and third slide events occurred very close together approximately 7000 years ago (Best 2003). The three slide events together moved a total of 5580 cubic kilometres of material and covered an area of 34000 square kilometres (Bugge et al. 1987). The average slope from the top of the upper headwall to the abyssal plain at 2800m depth is less than 0.6°. Over large parts of the area the inclination of the major slip surfaces is less than 0.4° (Kvalstad et al. 2002).

The failure surface of the first Storegga slide is coincident with the base of the gas hydrate stability zone. Likewise, the second Storegga slide area is supported by a well-defined bottom-simulating reflection (BSR) identified on seismic profiles from the northern flank of this slide (Bouriak et al. 2000).

The cause of failure is not entirely understood but numerous potential causes are currently being investigated. The most likely cause has been identified as an earthquake that would have disturbed the weakly deposited marine clay sediment. However, the sheer magnitude and geometry of the slide implies that there is an additional mechanism that aided such a massive movement of material. This added mechanism has been arguably identified as being gas hydrates located throughout the area of the slide.

3.2 The Cape Fear Slide

The Cape Fear landslide is a large and well-documented slide on the U.S. Atlantic continental margin that has been described by Popenoe et al. (2001). The landslide occurred on the continental slope and rise southeast of Cape Fear, North Carolina at 2600-meter water depth. The amphitheatre-shaped headwall scarp was 120m high and approximately 50 km long.

This landslide is considered to be unique to the Atlantic continental margin, because of the extruded salt diapir, and the presence of gas hydrates in the shallow subsurface (Popenoe et al. 2001). Both the intrusion of salt (Cashman and Popenoe 1985) and decomposition of the gas hydrate caused by past global warming or sea level decrease (Carpenter 1981; Paull et al. 1989); have been proposed as possible causes of the slope failure. A gas hydrate layer that has free gas trapped beneath much of its length is present throughout the area of the crest of Blake Ridge and beneath the continental slope and upper rise off North Carolina.

A seismic-reflection profile which reveals the deeper geologic structure of the slope beneath and adjacent to the landslide complex shows that upslope of the lower headwall scar there are a series of slip planes that are interpreted as a zone of relatively weak strata (Popenoe et al. 2001). This zone of weakness is coincident with the base of a discontinuous gas hydrate. There are numerous potential factors that collaborated within the area of the Cape Fear slide to have caused slope failure. The area is seismically active with large earthquakes happening in the region. The presence of numerous intrusive salt diapers, that by forcing their way through the strata, caused weakening of the layers and an accumulation point for free gas. Along with the presence of a large uniform gas hydrate layer where the base is coincident with the location of the slope failure slip planes. It would be likely that each of these factors combined together to cause the main Cape Fear slide and frequent minor slides along the Atlantic coast of the U.S.

3.3 Beaufort Sea Margin

The area of the Beaufort Sea margin has numerous slides all along the shelf (Grantz and Dinter 1980). Kayen and Lee (2001) describe the zone of slope instability extending from water depths of 200 to 400 meters at the shoreward edge to depths in excess of 2,000m. The areas of slope failures typically lie in a region underneath gas hydrate. The gas hydrate layer, interpreted from seismic-reflection profiles, extends beneath the sea floor between 400 to over 2000m in depth (Kayen and Lee 2001).

Given the geometry and sediment physical properties of the continental slope, the amount of excess pore-water pressure that will cause slope failure can be calculated. Kayen and Lee (2001) have determined the range of pressures to trigger slope failure of a 100 and 200m thick sedimentary deposit on a 5-degree sea-floor slope, typical of the Beaufort margin. These ranges are exceeded by the estimated values of pore pressure created by dissociation of gas hydrates.

Sampling from zones of slope failure indicates that the sediments are more clayey than sandy giving rise to the excess pore pressures necessary to cause failure (Kayen and Lee 2001). It has been concluded that for many of the deposits on the Beaufort Slope, excess pressure generation at the base of the gas-hydrate zone during Pleistocene drops in sea level was sufficient to initiate a sea floor landslide.

3.4 The Blake Ridge Collapse

Blake Ridge is located off the Atlantic Coast of the United States and is of interest for two reasons: 1) it appears to have the largest concentration of gas hydrates on the continental margin of the Eastern United States; 2) the Blake Ridge area collapse has occurred with no landsliding (Dillon et al. 1998).

Seismic reflection profiles of the Blake Ridge show the resulting depression at the crest of Blake Ridge. These faults consistently extend from the sea floor to approximately the base of the gas hydrate stability zone and occurred in a surface layer about 400-500m thick (Dillon et al. 1998). It is noted that the ridge has not been deformed by any extension or outward movement of the flanks and no sliding has taken place. Most of the faults extend to the gas hydrate layer but none of them extend beyond that base (Dillon et al. 1998).

Three sites along the Blake Outer Ridge have been drilled on the crest of the Blake Ridge up to a depth of 750m below the sea floor. The drillings have confirmed the presence of gas hydrates within the sediments composed of mainly greenish clays (Thiery et al. 1998). These hydrated cemented clays would act as a sufficient barrier to pore pressure dissipation thereby reducing the effective stress and reducing stability. It is believed that free gas, from migrating gas or gas hydrate dissociation, accumulated underneath either a hydrate layer or low permeable sediment at the crest of the ridge until the excess pressure exceeded the overburden pressure resulting in collapse.

3.5 Discussion of Case Studies

Through the analysis of the preceding case studies it has been shown that gas hydrates have a potentially adverse affect on submarine slope stability. Each case had gas hydrates in the vicinity of the slope failure confirmed by either direct or indirect methods. Each case had certain possible triggering mechanisms that either included gas hydrate dissociation directly, through loss of sediment strength and increased pore pressures, or indirectly where the decomposed hydrate released gas into a slope and they impacted the stability upslope. As a result it can be seen that gas hydrates may not single handedly reduce the stability sufficiently for failure to occur, but in conjunction with other factors hydrate decomposition may adversely affect submarine slope stability. More clearly demonstrated is that the presence of gas hydrates within the sediment of a slope has an influence that is not completely understood.

4. GAS HYDRATE MODEL

To evaluate the excess pore pressure resulting from gas hydrate dissociation the material model developed by Grozic and Kvalstad (2001) was used. If the temperature/heat transport and the pressure change processes are fast compared with pore pressure dissipation processes, the excess pore pressure and reduction in effective stress can be estimated as follows:

$$-0.13\cdot n\cdot(1-S_w)+\frac{164.6\cdot n\cdot(1-S_w)\cdot 1atm\cdot T_{eq}}{298.15K\cdot p_{eq}}=-\frac{\Delta\sigma'}{M(\sigma')} \quad [1]$$

where n is the soil porosity, S_w is the degree of water saturation, ($1\text{-}S_w$) is the degree of saturation of gas hydrates assuming no free gas in the hydrate stability zone, T_{eq} is the equilibrium temperature of gas hydrate in K, p_{eq} is the equilibrium pressure of gas hydrate in atm, $\Delta\sigma'$ is the change in effective stress caused by melting of gas hydrate, and M is the confined compression modulus of soil. The first term represents the difference between the hydrate volume and melted water volume (1.0 m^3 – 0.87 m^3), the second term represents the volume of released gas at equilibrium temperature and pressure and the final term represents the volume change of the soil.

The confined compression modulus,

$$M=m\cdot\sigma' \quad [2]$$

where m is the unload modulus number, is difficult to estimate for submarine sediments. The right hand side of Equation 1 represents the volume change, ΔV, due to a change in effective stress similar to consolidation, where:

$$\frac{\Delta V}{V}=\frac{\Delta e}{1+e}=a_v\cdot\Delta\sigma' \quad [3]$$

where a_v is the coefficient of compressibility. Therefore, the confined compression modulus is related to the compressibility by,

$$M=\frac{1}{m_v}=\frac{1+e_o}{a_v} \quad [4]$$

where m_v is the modulus of volume compressibility. Dissociation results in a decrease in effective stress therefore the swelling index is most applicable. The coefficient of compressibility, a_v, can be related to the swelling index, C_s, as

$$a_v=\frac{0.434\cdot C_s}{\sigma'} \quad [5]$$

As a result Equation 2 becomes:

$$M=\frac{(1+e_o)\cdot\sigma'}{0.434\cdot C_s} \quad [6]$$

Therefore, given a water content and assuming a specific gravity, G_s, and a degree of saturation of 100% void ratio can be calculated. Then using the correlation developed by Wroth (1979) for a given plasticity index, PI, the swelling index can be approximated from:

$$C_s=\frac{PI\cdot G_s}{200} \quad [7]$$

Assuming undrained behaviour, the change in pore pressure can now be calculated from and Equation 1 can be re-written as:

$$\Delta\sigma'=-\Delta u=\frac{(1+e_o)\sigma'}{0.434\cdot C_s}\cdot n\cdot(1-S_w)\left[0.13-164.6\frac{T_{eq}}{298.15}\frac{1atm}{p_{eq}}\right] \quad [8]$$

5. SIMULATED INFINITE SLOPE

Submerged slopes along the continental margin are usually long with a slight incline, typically between one to ten degrees. Therefore, the use of infinite slope equations as a preliminary analysis should prove to be acceptable, as the length of slope is significantly larger than the depth to failure surface. The infinite slope equations neglect the resisting forces along the sides of the failure surface; the effect of this assumption will be the subject of further analysis.

The effect of gas hydrates on the stability of a simulated slope was analyzed with the infinite slope equations with pore pressures calculated from Equation 8. Using typical values of unit weight of soil, friction angle, and cohesion, then varying certain parameters, such as slope angle, water depth, depth of hydrate below seabed, and percent hydrate, the impact on the factor of safety was calculated. The thickness of the hydrate stability zone (where hydrates can exist) is influenced by the seabed temperature and the geothermal gradient which have been set to 2 degrees Celsius and 2 degrees Celsius per 100m, respectively, for these analyses.

The first analysis investigated the effects of water depth on the factor of safety. Assuming a depth to hydrate below seabed of 200m and 3% hydrate the factor of safety was calculated at discrete points at increasing water depths. The factor of safety drops to zero once the pressure has become high enough for gas hydrates to exist (see Figure 3). This drop to zero factor of safety indicates that the pore pressure generated by complete dissociation of the 3% hydrate is greater than the total stress acting at that point therefore no resistance to sliding is provided. The factor of safety then begins to rise as the overburden stress increases, which decreases the magnitude of excess pore pressure generated by melting gas hydrates.

The second analysis involved varying the depth of hydrate below seabed and calculating the factor of safety. Assuming a water depth of 150m and hydrate content of 3%, and then increasing the depth of hydrate below the seabed similar results are produced (see Figure 4). This figure illustrates that at lower depths below seabed gas hydrates can not exist because of insufficient pressure and at greater depths the hydrates do not exist because the temperature is too high for formation. The factor of safety at these two ends are the same for a given slope angle, as the infinite slope equations are not influenced by depth to failure surface. From 200m to 400m below the seabed the factor of safety is again reduced to zero as the pore pressures generated from dissociated hydrates are greater than the total stress and provide no resistance to sliding. The factor of safety then begins to rise as the overburden begins to exert more confining stress on the pressures generated by hydrate melting.

It would be reasonable to assume that the factor of safety would, in actuality, be higher than shown in Figure 4 at the greater depths below seabed because of the resistance of the ends being neglected. The significance of incorporating end effects on the factor of safety has yet to be determined and will be examined further. However, when examining a slope as a whole, the length will likely provide significantly more effects on resistance than the shorter sides of the failure surface.

The third analysis investigated the impact of hydrate content on the factor of safety of a simulated slope. Assuming a hydrate depth of 200m below the seabed and varying from 150m to 530m water depths an average factor of safety was calculated (see Figure 5). This was accomplished by summing the resisting and driving forces from the infinite slope equations at 20 discrete points along the simulated slope at increasing water depths for various slope angles. It can be seen that with increasing hydrate content the factor of safety for a given slope angle drops quickly and by four percent hydrate all the slopes have failed.

It should be noted that these results stem from complete hydrate dissociation along the entire length of the slope, which could be considered a worst case scenario. Gas hydrate in a real slope may not all dissociate simultaneously along the entire length, perhaps this would only occur in the case of a uniform sea level drop or temperature fluctuation. An actual case may have only certain sections of the hydrate layer dissociate, such as locations at the edge of the hydrate stability zone. Or, dissociation in a continuous hydrate layer may only occur in a certain areas, such as a result of temperature increases around a conductor casing of a petroleum platform. Another case could be that hydrates may only exist in nodules along a slope and produce pockets of increased pore pressures upon dissociation. These effects and conditions will need to be investigated further. However, this investigation has clearly shown that gas hydrates may have a significant effect of slope stability and thus should be considered during analyses.

6. CONCLUSIONS

This investigation has identified that gas hydrate dissociation can have a significant impact on slope stability, especially at lower magnitudes of overburden. At these lower stresses the pore pressure generated by hydrate dissociation exceeds the total stress and result in little to no resistance. At greater values of total stress the pore pressure no longer dominates the calculations, but still results in a reduction in stability. All these results are calculated using infinite slope equations, which neglect the resistance of the ends of the failure surface. Further investigation is required to establish the acceptability of the infinite slope equations when deeper failure surfaces are considered. Other areas that require further research are to what extent and percentage do gas hydrates need to be present and dissociate to continue to impact stability.

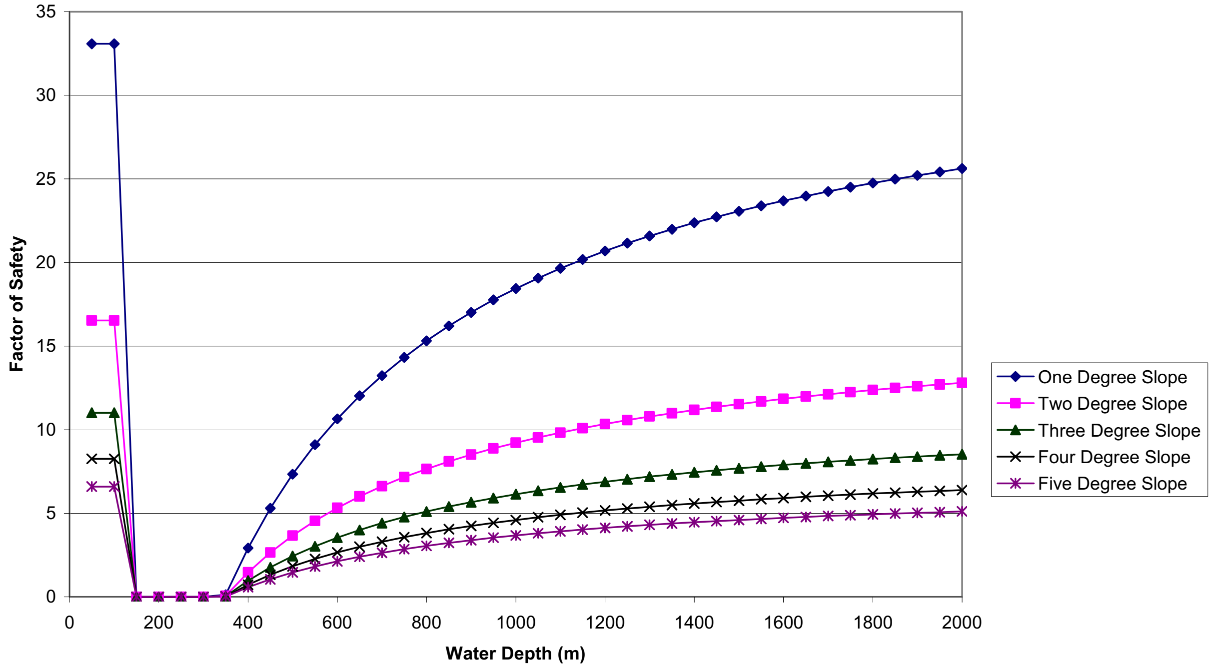

Figure 3. Factor of Safety for Hydrate Layer 200m Below Seabed Under Simulated Gas Hydrate Dissociation
(Friction Angle = 30, Cohesion = 0, 3% Hydrate)

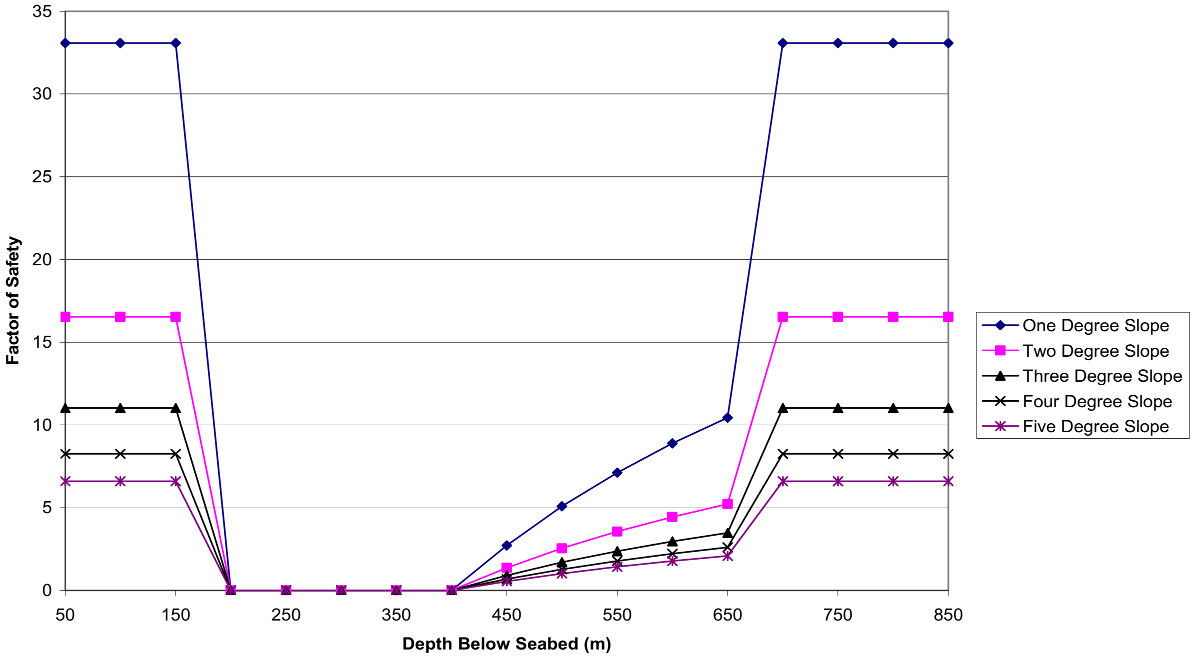

Figure 4. Factor of Safety in 150m of Water Under Simulated Gas Hydrate Dissociation
(Friction Angle = 30, Cohesion = 0, 3% Hydrate)

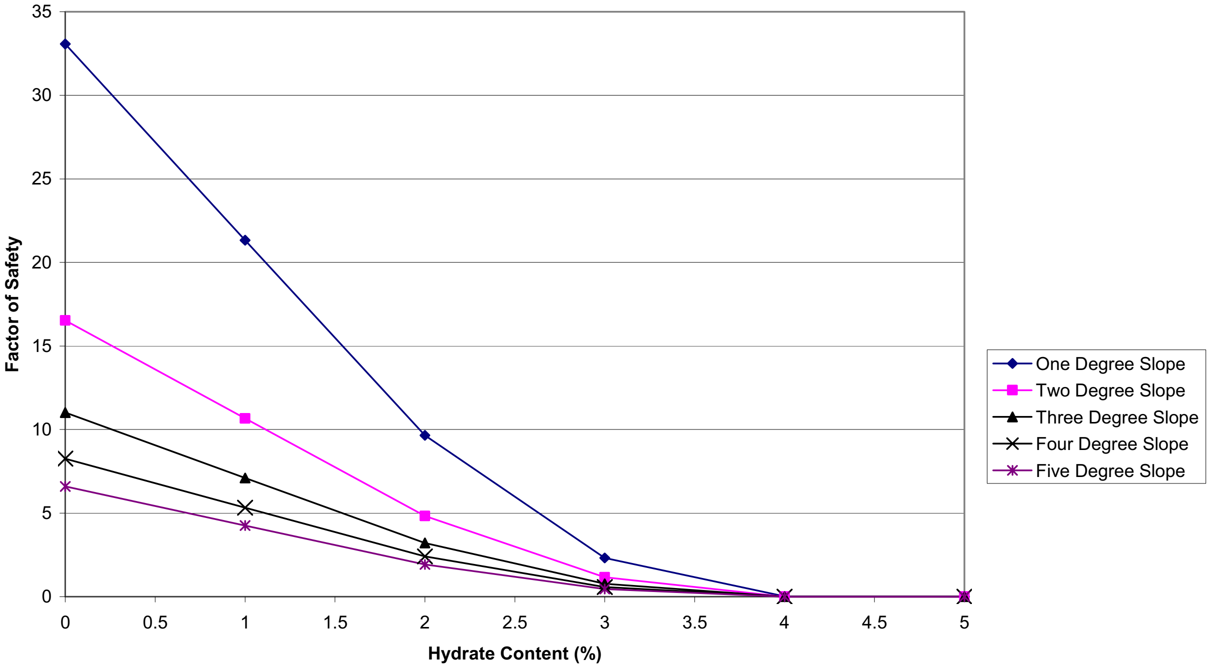

Figure 5. Factor of Safety Using Summation of Discrete Points on a Simulated Slope for Water Depths Ranging from 150m to 530m (Hydrate Layer 200m Below Seabed, Friction Angle = 30, Cohesion = 0)

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