Addendum to Mudslides during Hurricane Ivan and an Assessment of the Potential for Future Mudslides in the Gulf of Mexico

by

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I. INTRODUCTION

In the final project report (OTRC 2007), we identified a concern that our characterization of the wave-loading hazard was over simplistic because it assumed that a "one-to-one relationship between maximum wave height and peak spectral period". This assumption does not consider that other locations in a given storm can have lower wave heights with the same peak spectral period whose heights may also be large enough to cause a mudslide. This will tend to underestimate the frequency of occurrence of a mudslide, and accordingly we recommended that the impact of this assumption on overall risks should be investigated.

Figure 37 from OTRC (2007) is included again below as Figure 1 to demonstrate this issue. The curve labeled "Average" was determined from hindcast hurricane maxima in many hurricanes throughout the Gulf, and was used to determine the one-to-one relationship between maximum wave height and peak spectral period. The hindcast maxima generated by Ivan and Katrina at locations in the Delta are included in the plot. Here we have added a sketch of the wave height distributions across Ivan and Katrina's paths that show the relative positions of the eye and maximum wave heights for each storm relative to the delta area. This figure shows that the peak periods for Ivan's waves in the Delta area were the same as the peak period of the maximum wave height generated by Ivan near its eye some 90 miles to the east. Similarly, Katrina generated waves that occurred away from its eye with the same peak periods as the maximum wave heights but with heights less than the storm maximum. By characterizing the maximum height-peak period relationship only by points along the average curve we see that we omit some long period waves with smaller heights that could cause mudslides. And since seafloor stability and mudslides are related to both wave height and period, we are potentially omitting situations that could cause mudslides.

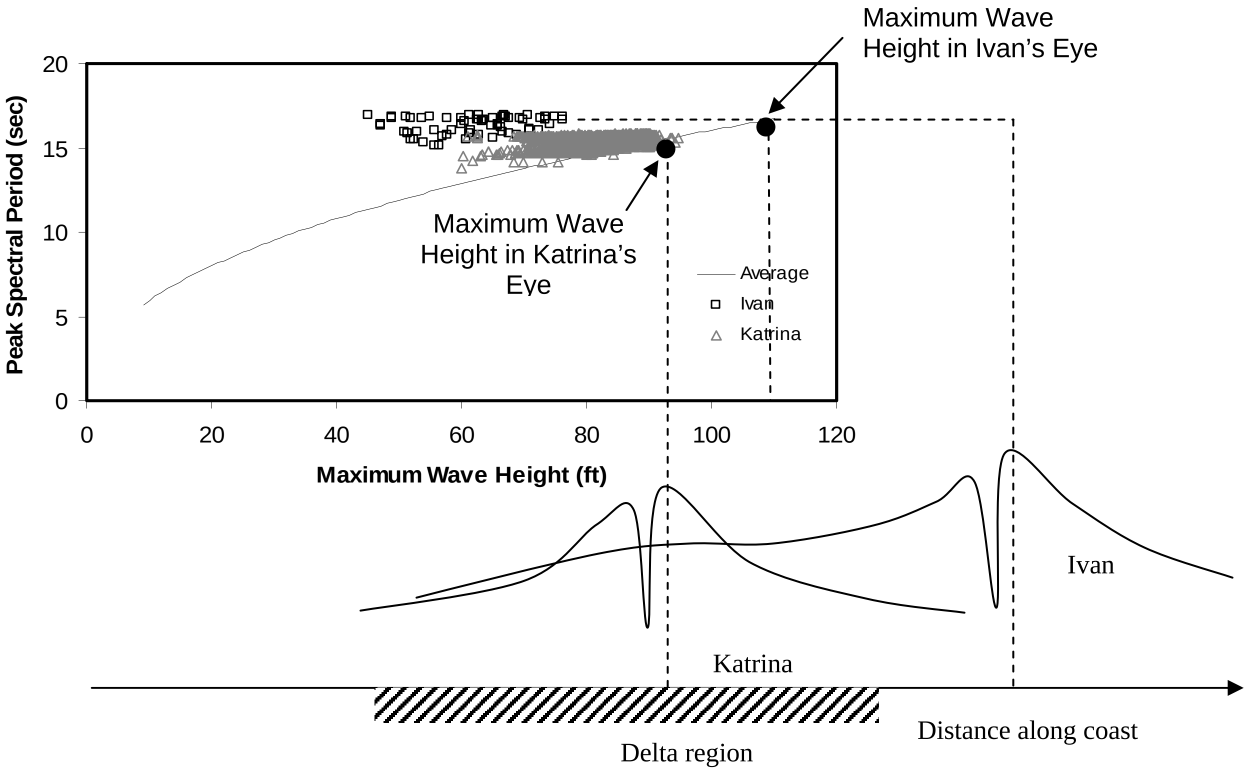

Figure 1. Relationship of peak spectral period with maximum wave height in the Delta for Hurricanes Ivan and Katrina, and the average relationship for historical hurricanes (Figure 37 from OTRC 2007)

II. REVISED APPROACH TO CHARACTERIZE WAVE PERIODS FOR MUDSLIDE RISK IN DELTA

The revised approach to characterize the wave hazard is developed as follows. First, we assume that the relationship between wave period and wave height in the API criteria is appropriate provided that the wave height corresponds to the eye of the storm (Figure 2). Our analysis of the available hurricane data supports this assumption. Therefore, if we know the size of the waves in the eye in deepwater, then we can estimate the period for these waves as well as for smaller waves at other locations in the storm (and even at other water depths – note that this assumption about the period of the waves in all water depths corresponding to those for the waves in deepwater is implicit in the API guidelines). The key then is to develop a probability distribution for the waves near the eye that is conditional on a particular wave height occurring in the Delta. In this way we can establish the joint probability of possible wave heights and periods in the Delta.

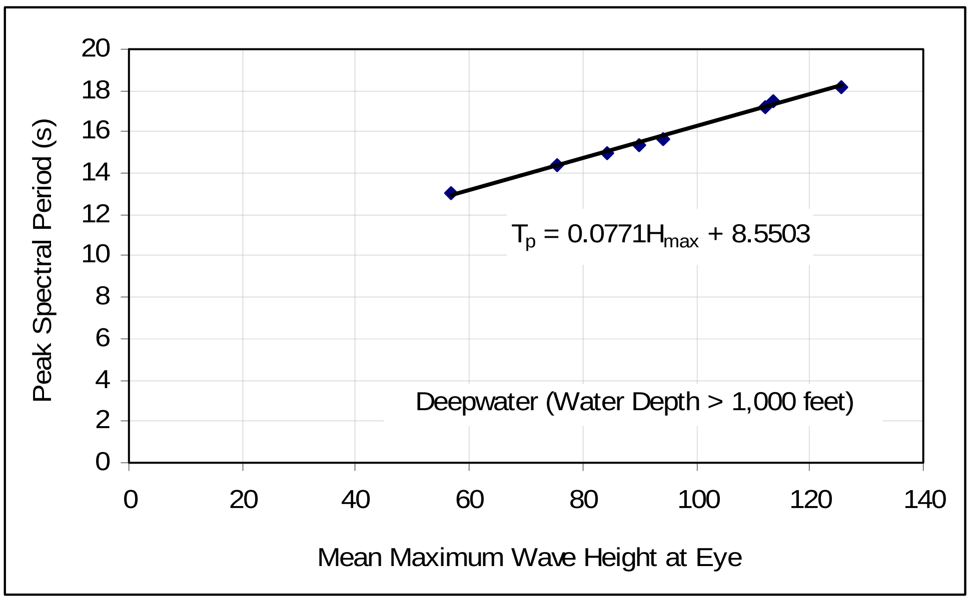

Figure 2. API relationship between peak spectral period and mean maximum wave height in deepwater

Next, if a particular wave height occurs in the Delta, h_{delta}, it means that the waves in the storm are at least as big as those in the Delta, or $H_{anywhere} \geq h_{delta}$ (e.g., in Katrina $H_{anywhere} = h_{delta}$ while in Ivan $H_{anywhere} > h_{delta}$). We can then use the API frequencies for wave heights at any location in deepwater (Figure 3) to establish the conditional probabilities for wave heights near the eye in deepwater, H_{eye}, as follows:

$$P\left(H_{eye} = h_{eye} \middle| H_{delta} = h_{delta}\right) = P\left(H_{eye} = h_{eye} \middle| H_{anywhere} \geq h_{delta}\right)$$
$$= \frac{P\left(H_{anywhere} \geq h_{delta} \middle| H_{eye} = h_{eye}\right) P\left(H_{eye} = h_{eye}\right)}{P\left(H_{anywhere} \geq h_{delta}\right)}$$

Note that we are discretizing the possible wave heights here (Fig. 3) into rather large bins for simplicity. Therefore, the above equation is expressed as follows to reflect this discretization:

$$P\left(H_{eye} = h_{eye} \middle| H_{delta} = h_{delta}\right) = P\left(H_{eye} = \frac{h_{eye,a} + h_{eye,b}}{2} \middle| H_{delta} = \frac{h_{delta,a} + h_{delta,b}}{2}\right)$$
$$= P\left(h_{eye,a} < H_{eye} \leq h_{eye,b} \middle| H_{anywhere} \geq h_{delta,a}\right)$$
$$= \frac{P\left(H_{anywhere} \geq h_{delta,a} \middle| h_{eye,a} < H_{eye} \leq h_{eye,b}\right) P\left(h_{eye,a} < H_{eye} \leq h_{eye,b}\right)}{P\left(H_{anywhere} \geq h_{delta,a}\right)}$$

where the subscripts a and b represent the lower and upper bounds, respectively, for each bin in Figure 3. We readily could use the same approach with smaller bin sizes or even a continuous distribution, if appropriate or necessary.

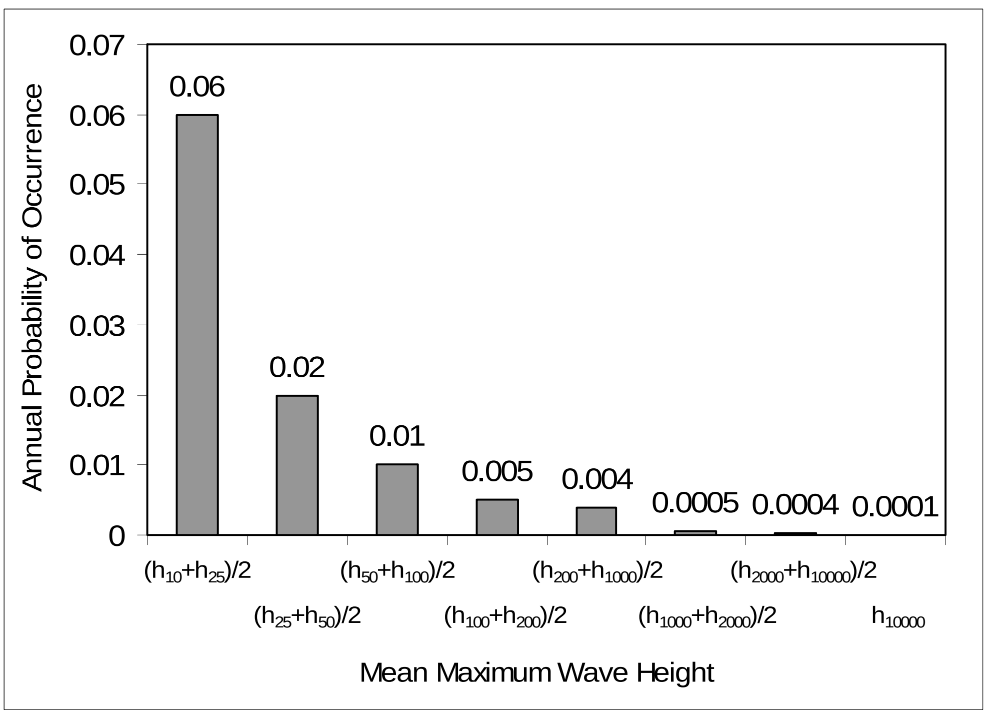

Figure 3a. Probability distribution for maximum wave height at any location in deepwater (taken from API criteria) – expressed in terms of return period for waves

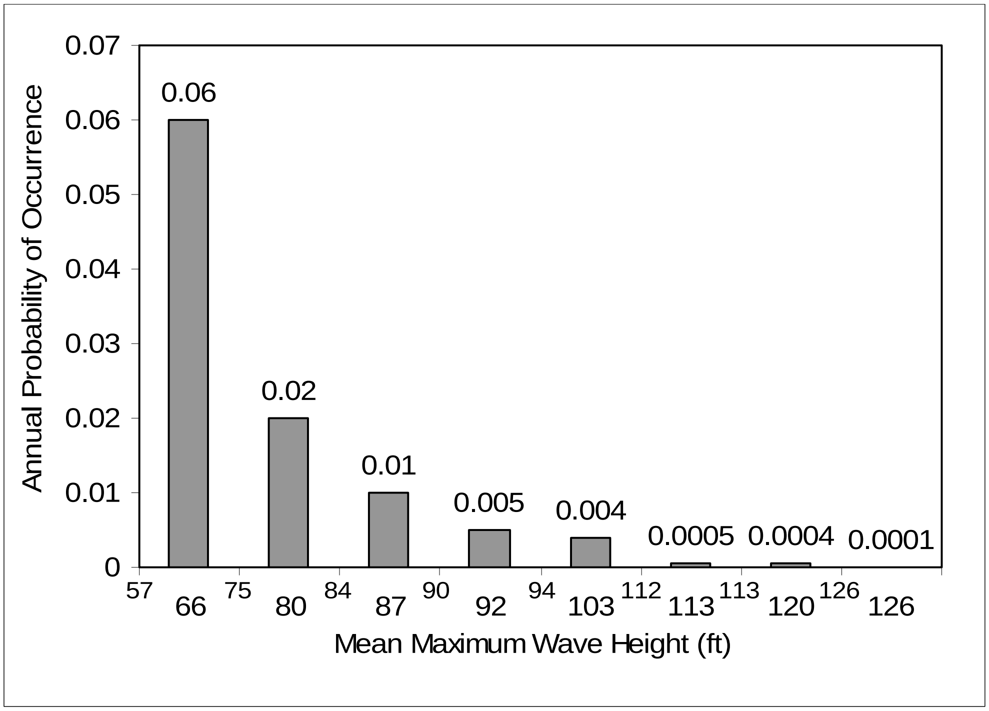

Figure 3b. Probability distribution for maximum wave height at any location in deepwater (taken from API criteria) – expressed in terms of wave height

Finally, we use Figure 2 to relate the peak spectral period for a given wave height near the eye to a probability of occurrence for a given wave height in the Delta:

$$P\left(T_p = 0.0771 h_{eye} + 8.5503 \middle| H_{delta} = h_{delta}\right) = P\left(H_{eye} = h_{eye} \middle| H_{delta} = h_{delta}\right)$$

To illustrate, consider that the maximum waves in deepwater at a location in the Delta are between 57 and 75 feet (comparable to Ivan). This range of wave heights is represented by a 66-foot maximum wave height in the discrete bins (Fig. 3b). The conditional probabilities for the wave height at the eye of the storm are calculated as follows:

$$P\left(H_{eye} = 66\text{ ft} \middle| H_{delta} = 66\text{ ft}\right) = P\left(H_{eye} = \frac{57+75}{2}\text{ ft} \middle| H_{delta} = \frac{57+75}{2}\text{ ft}\right)$$

$$= P\left(57 < H_{eye} \le 75\text{ ft} \middle| H_{anywhere} \ge 57\text{ ft}\right)$$

$$= \frac{P\left(H_{anywhere} \ge 57\text{ ft} \middle| 57 < H_{eye} \le 75\text{ ft}\right) P\left(57 < H_{eye} \le 75\text{ ft}\right)}{P\left(H_{anywhere} \ge 57\text{ ft}\right)}$$

$$= \frac{1.0 \times 0.06}{0.06 + 0.02 + 0.01 + 0.005 + 0.004 + 0.0005 + 0.0004 + 0.0001}$$

$$= 0.06/0.10 = 0.60$$

$$P\left(H_{eye} = 80\text{ ft} \middle| H_{delta} = 66\text{ ft}\right) = 0.02/0.10 = 0.20$$

$$P\left(H_{eye} = 87\text{ ft} \middle| H_{delta} = 66\text{ ft}\right) = 0.01/0.10 = 0.10$$

$$P\left(H_{eye} = 92\text{ ft} \middle| H_{delta} = 66\text{ ft}\right) = 0.005/0.10 = 0.05$$

$$P\left(H_{eye} = 103\text{ ft} \middle| H_{delta} = 66\text{ ft}\right) = 0.004/0.10 = 0.04$$

$$P\left(H_{eye} = 113\text{ ft} \middle| H_{delta} 66\text{ ft}\right) = 0.0005/0.10 = 0.005$$

$$P\left(H_{eye} = 120\text{ ft} \middle| H_{delta} = 66\text{ ft}\right) = 0.0004/0.10 = 0.004$$

$$P\left(H_{eye} = 126\text{ ft} \middle| H_{delta} = 66\text{ ft}\right) = 0.0001/0.10 = 0.001$$

The resulting conditional probability distribution for the wave heights near the eye is shown in Figure 4, and that for the peak spectral period is shown in Figure 5. This result indicates that the most likely peak period is about 14 seconds (corresponding to the eye passing near the Delta). However, there is 10 percent chance that the peak period is greater than or equal to about 16 seconds, which is what it was during Ivan. Therefore, while not likely, an Ivan-like wave loading in the Delta is possible within this framework.

The conditional probability distributions for all of the possible deepwater wave heights in the Delta are shown in Figures 5 to 12. Also, the revised approach to characterizing wave hazard for mudslides is summarized in Figure 13. From the period, we can calculate the associated wave length and bottom pressure for each possible combination of wave height, period and bottom-pressure correction factor.

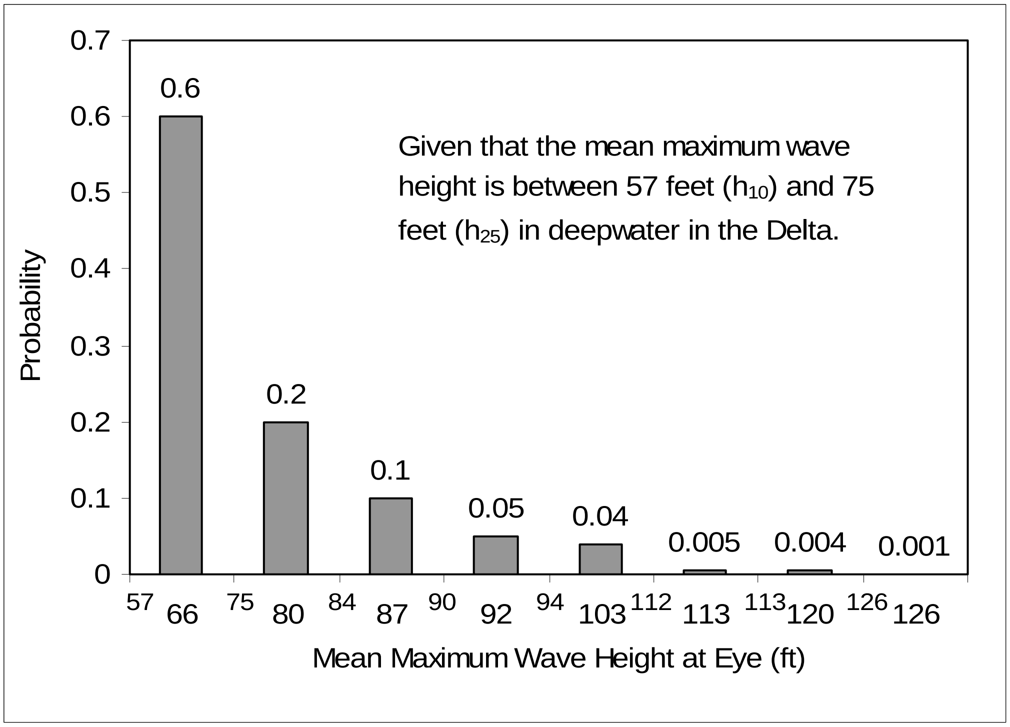

Figure 4. Conditional probability distribution for maximum wave height at eye given that the mean maximum wave height is between 57 and 75 feet in the Delta

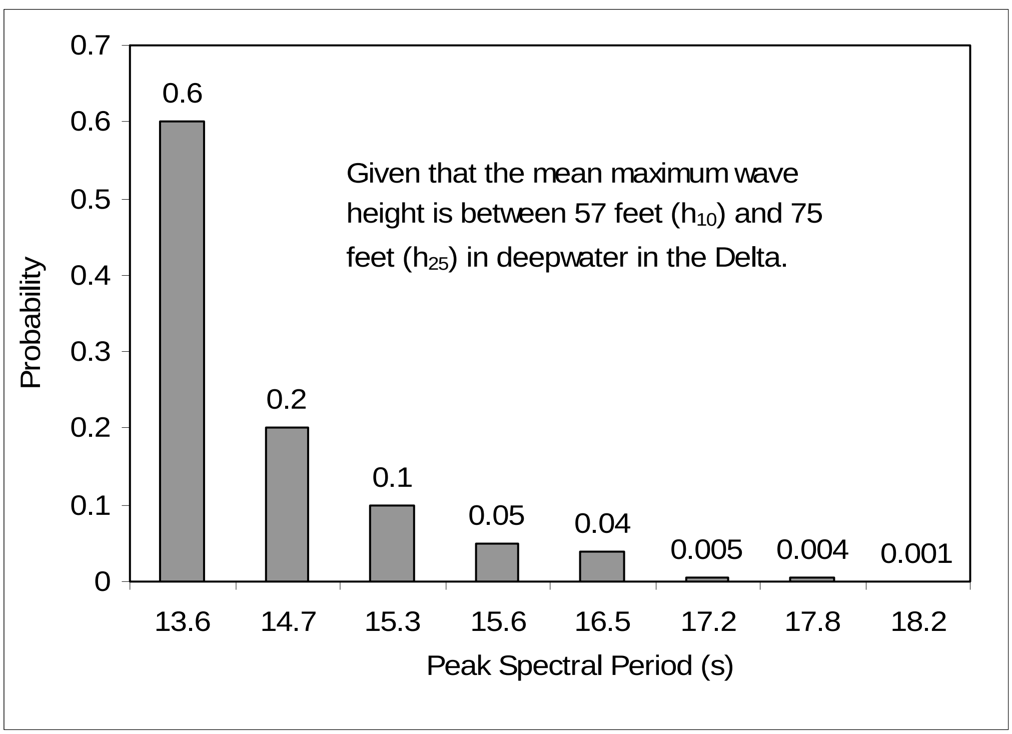

Figure 5. Conditional probability distribution for peak spectral period given that the mean maximum wave height is between 57 and 75 feet in deepwater in the Delta (or between the 10-year and 25-year return period values for any water depth in the Delta)

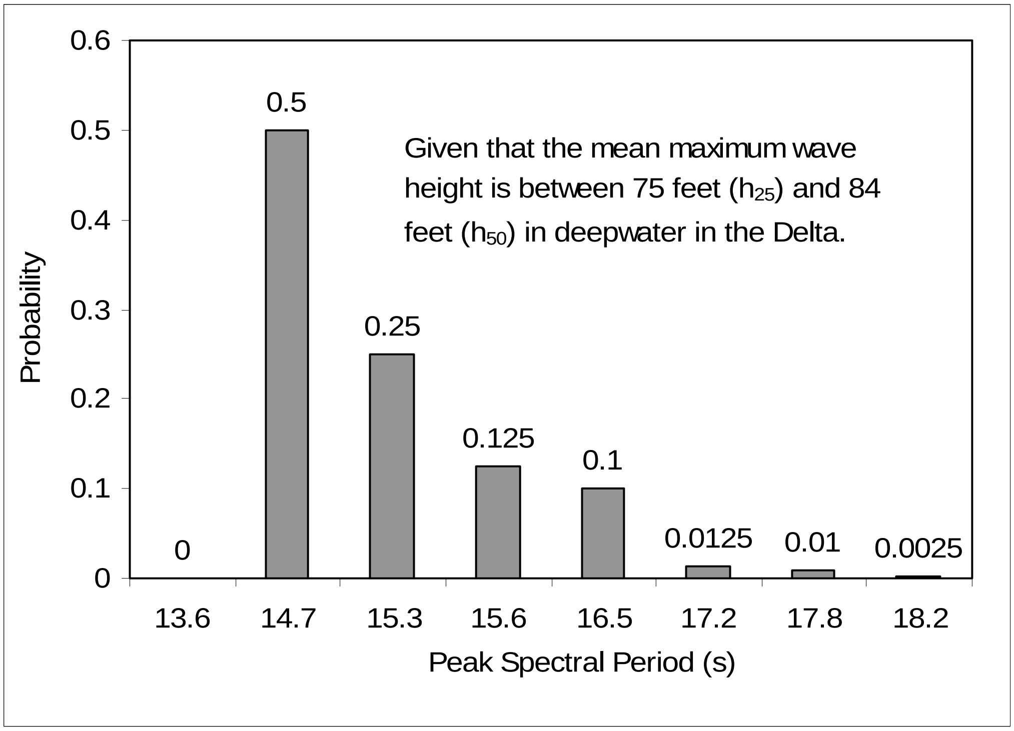

Figure 6. Conditional probability distribution for peak spectral period given that the mean maximum wave height is between 75 and 84 feet in deepwater in the Delta (or between the 25-year and 50-year return period values for any water depth in the Delta)

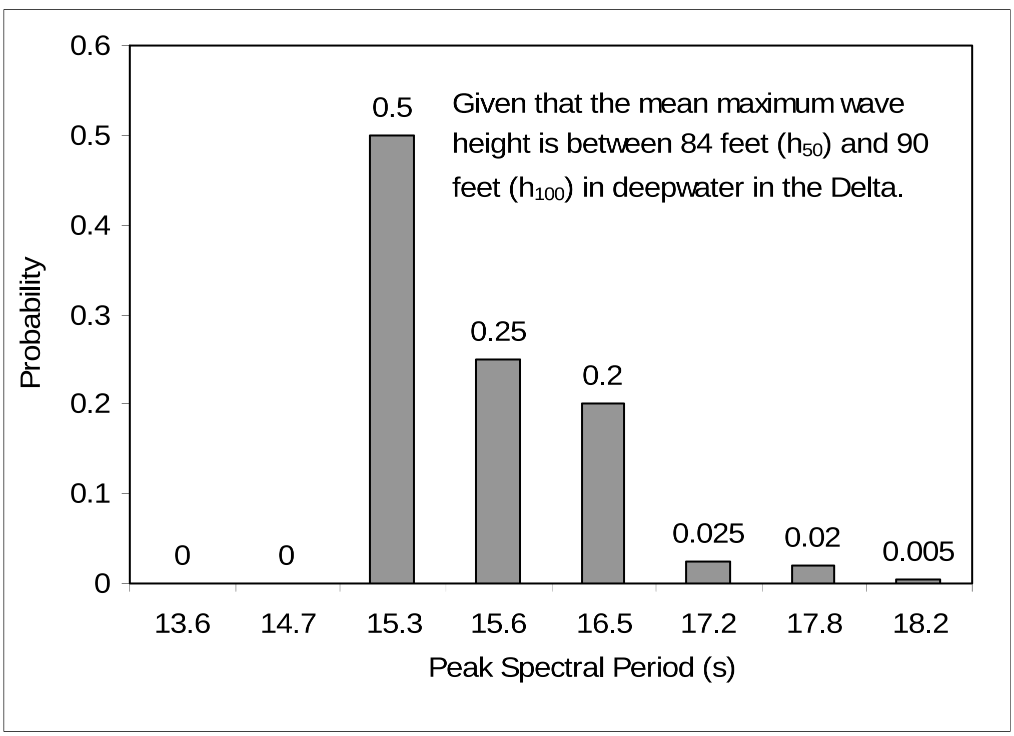

Figure 7. Conditional probability distribution for peak spectral period given that the mean maximum wave height is between 84 and 90 feet in deepwater in the Delta (or between the 50-year and 100-year return period values for any water depth in the Delta)

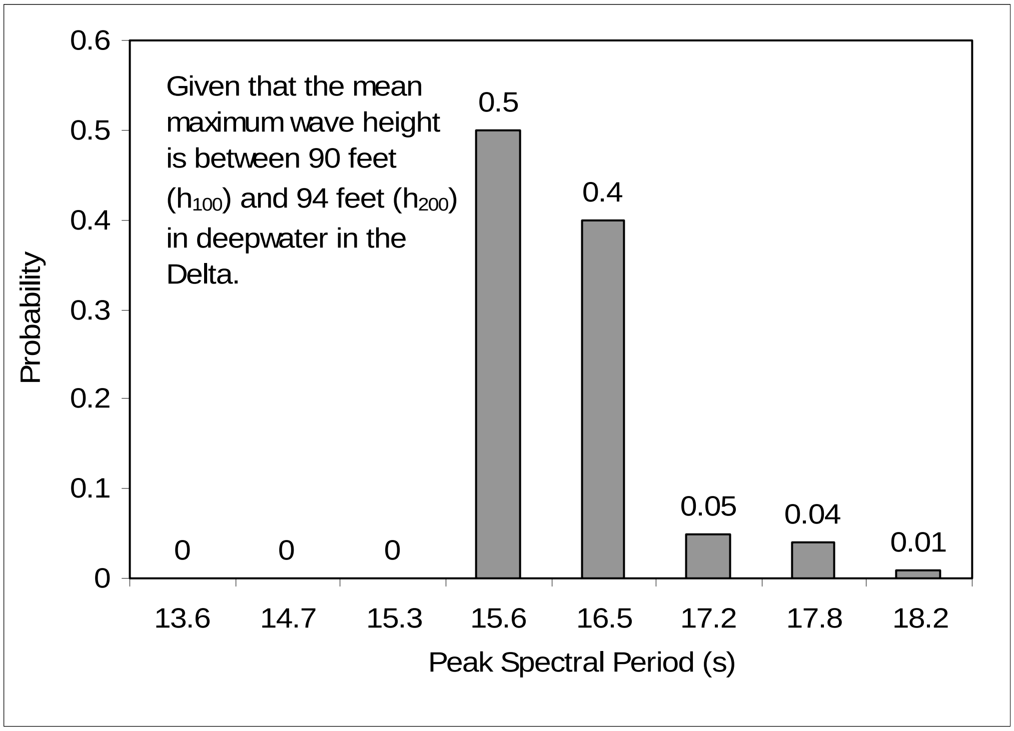

Figure 8. Conditional probability distribution for peak spectral period given that the mean maximum wave height is between 90 and 94 feet in deepwater in the Delta (or between the 100-year and 200-year return period values for any water depth in the Delta)

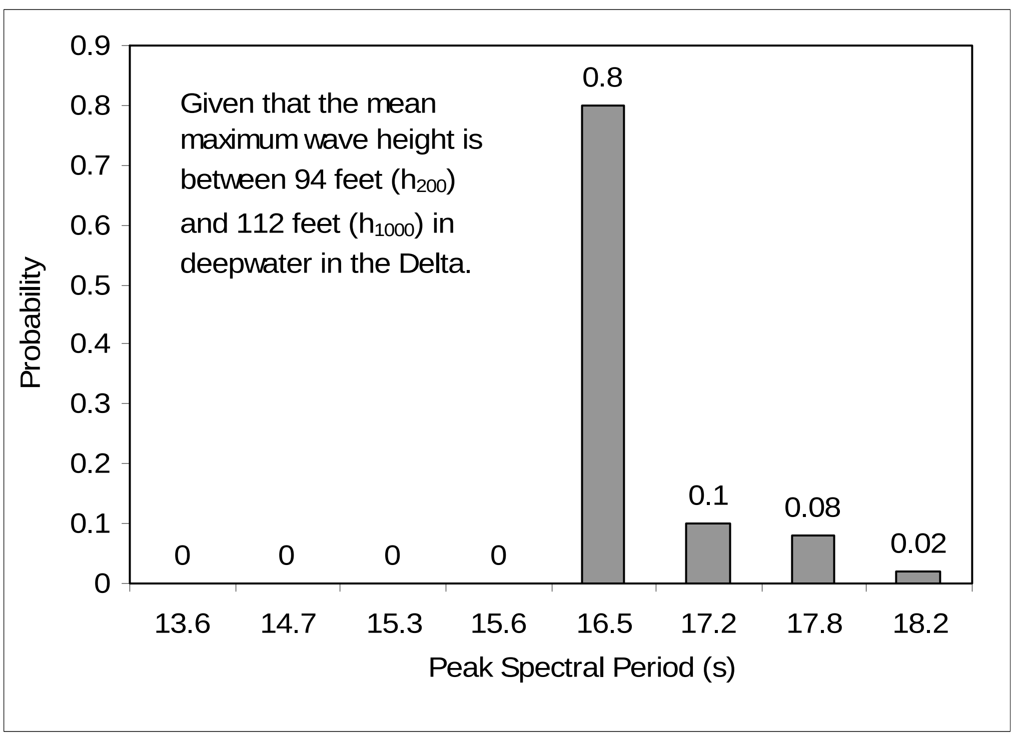

Figure 9. Conditional probability distribution for peak spectral period given that the mean maximum wave height is between 94 and 112 feet in deepwater in the Delta (or between the 200-year and 1000-year return period values for any water depth in the Delta)

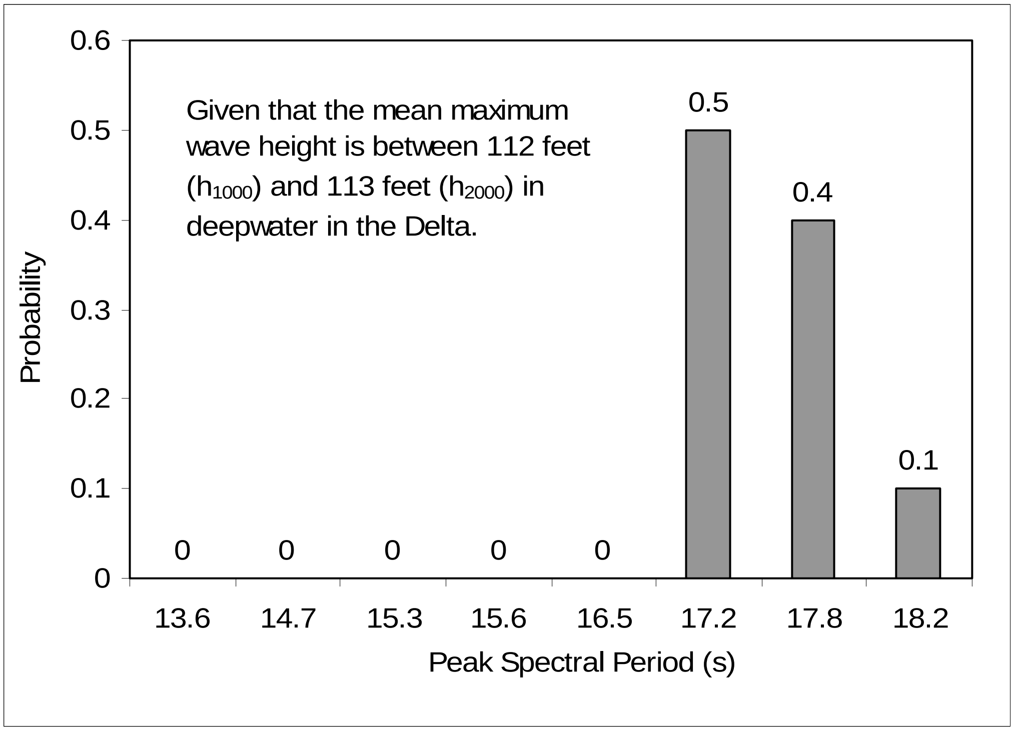

Figure 10. Conditional probability distribution for peak spectral period given that the mean maximum wave height is between 112 and 113 feet in deepwater in the Delta (or between the 1000-year and 2000-year return period values for any water depth in the Delta)

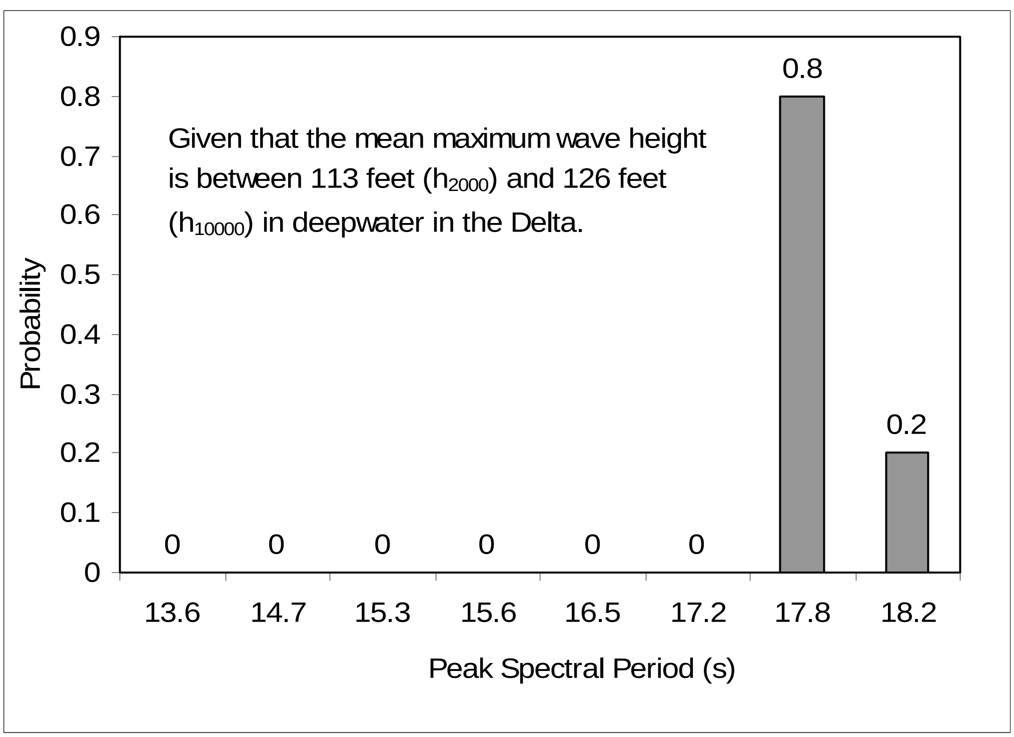

Figure 11. Conditional probability distribution for peak spectral period given that the mean maximum wave height is between 113 and 126 feet in deepwater in the Delta (or between the 2000-year and 10000-year return period values for any water depth in the Delta)

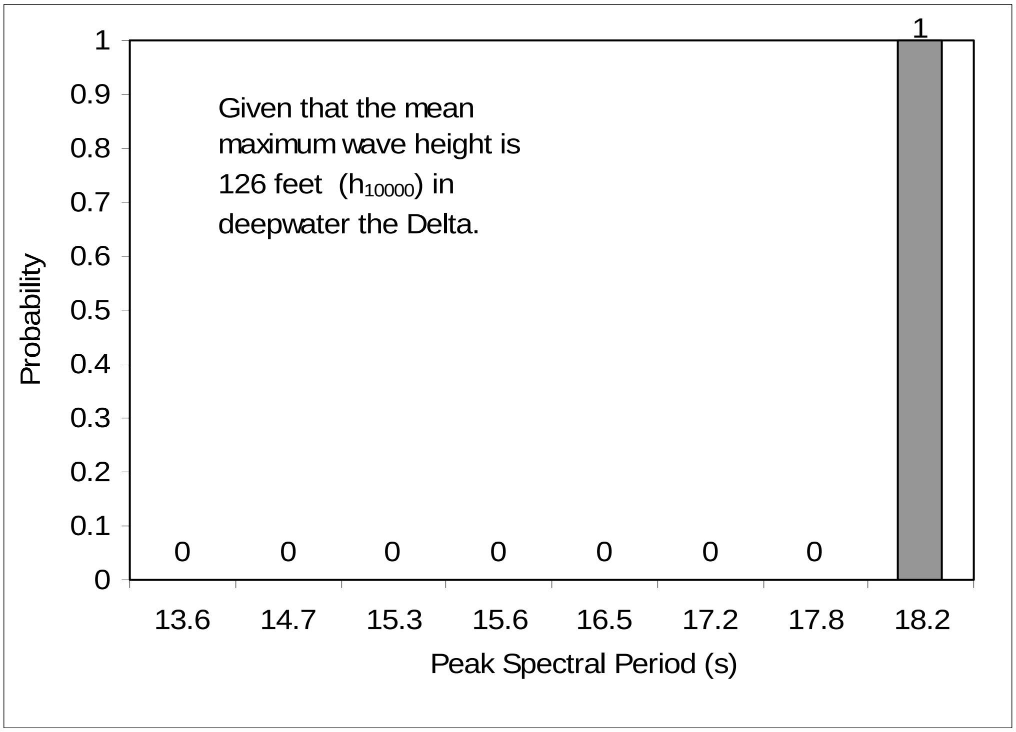

Figure 12. Conditional probability distribution for peak spectral period given that the mean maximum wave height is 126 feet in deepwater in the Delta (or the 10000-year return period value for any water depth in the Delta)

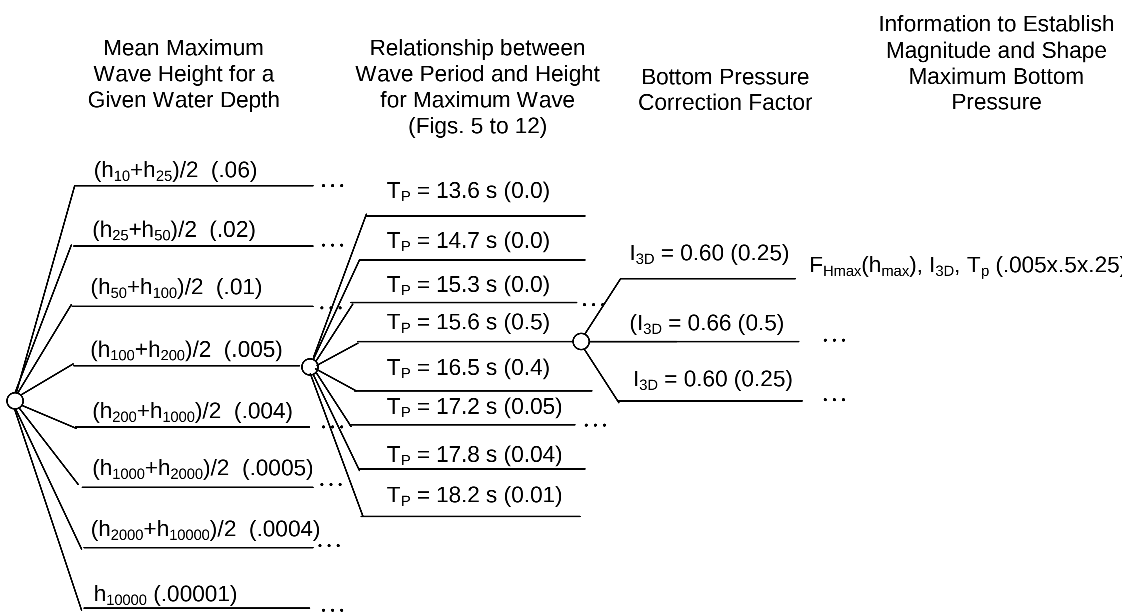

Figure 13. Event tree representing hazard for wave-induced mudslides (updated from Figure 73 in OTRC 2007)

III. RESULTS FROM REVISED APPROACH TO CHARACTERIZE WAVE PERIODS FOR MUDSLIDE RISK IN THE DELTA

The results from the risk analysis have been updated using this revised approach to characterize the wave hazard. Figures 14 and 15 compare results from the updated approach and the original approach. The effect of accounting for the possibility of longer-period, smaller waves is to increase the annual probability of failure at a point (a 4,000-foot by 4,000-foot area). The relative increase is the greatest at the locations with the smallest probabilities and is generally less than a factor of two. In terms of the return period, the updated approach produces smaller return periods (Figure 15). For return periods less than 30 years, the differences are negligible with at most about a 10 percent reduction in the return period. For return periods less than 100 years, the differences are relatively small; for example, the largest change is to reduce a return period of 100 years to about 70 years. The greatest changes are for return periods greater than 100 years, where the biggest differences are about 50 percent; for example a 1,000-year return period is reduced at most to a 500-year return period (Figure 15).

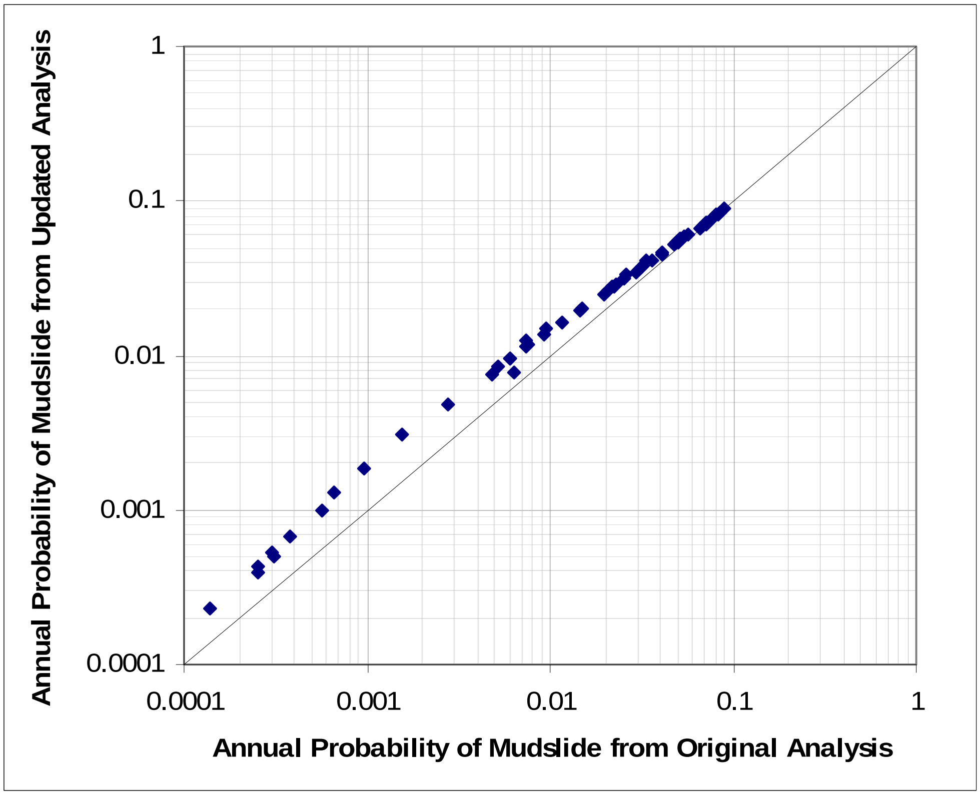

Figure 14: Comparison of annual probability for a mudslide at different points (4,000-foot by 4,000-foot areas) in the Delta using the updated versus the original approach for characterizing the wave hazard.

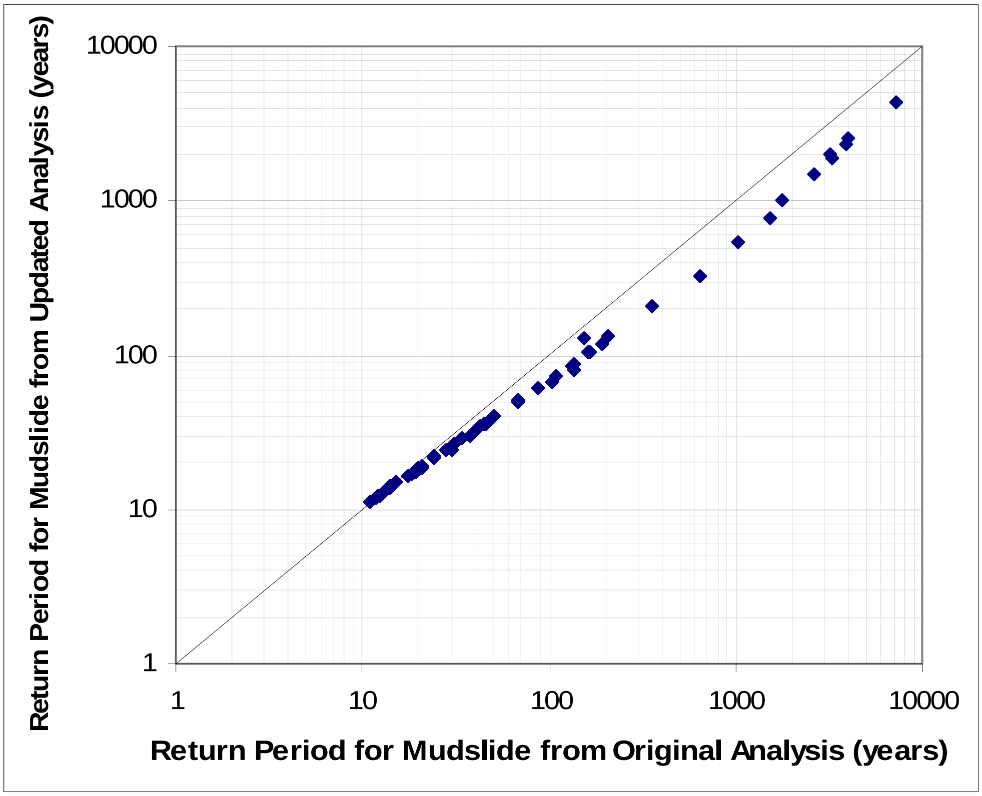

Figure 15: Comparison of return periods for a mudslide at different points (4,000-foot by 4,000 foot areas) in the Delta using the updated versus the original approach for characterizing the wave hazard.

Figures 16, 17 and 18 show updated versions of the "risk maps," Figures 77, 78 and 79 from the original project report (OTRC 2007). In order to discriminate differences in the regions and return periods of interest, the results on the updated risk maps are shown for return periods of less than 30 years (the typical design life for a production facility), between 30 and 100 years (the typical return period for design checks), between 100 and 1,000 years and greater than 1,000 years.

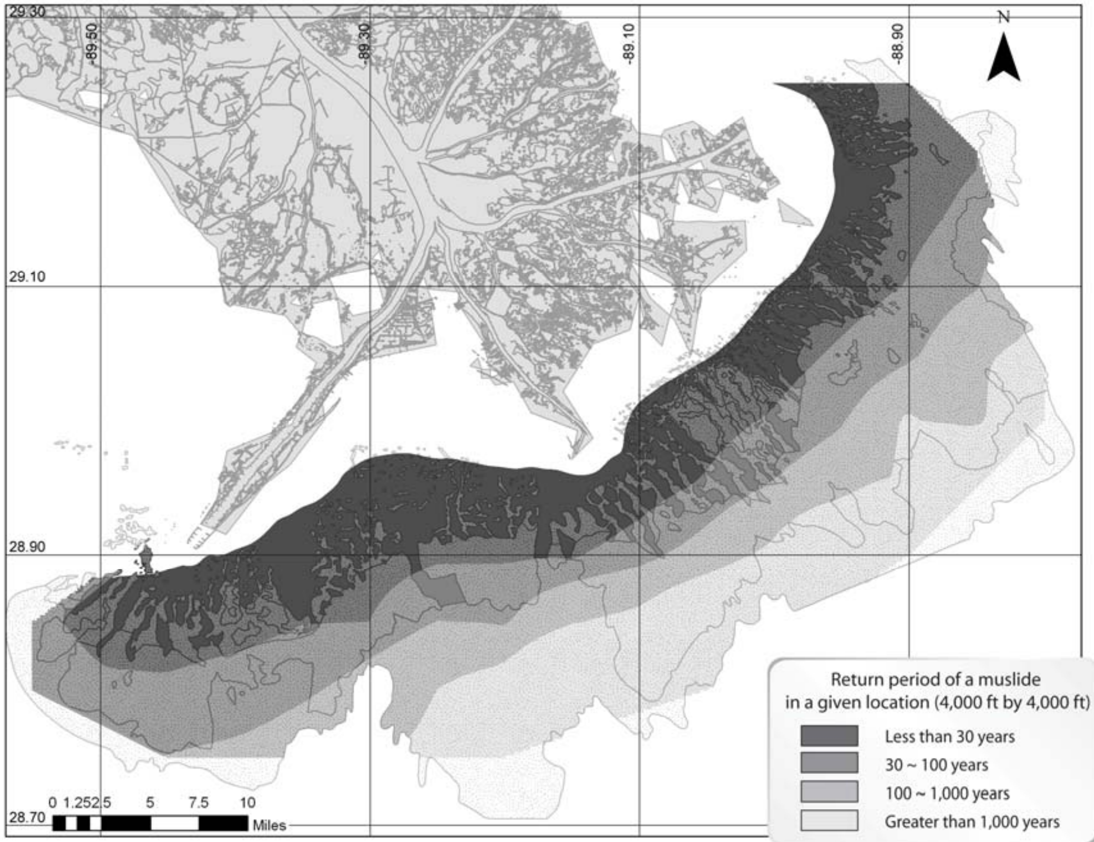

Figure 16: Return periods of a mudslide occurring at a point (4000 foot by 4000 foot area) (updated Fig. 77 from OTRC 2007)

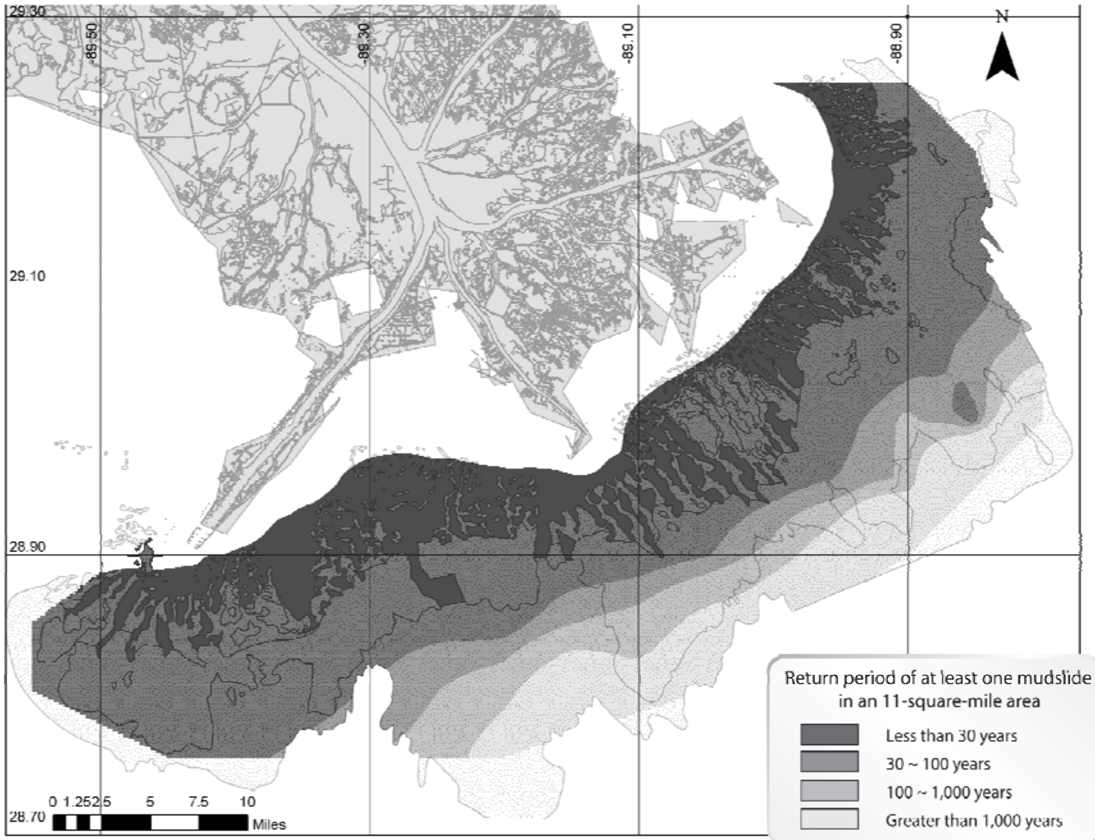

Figure 17: Return periods of at least one mudslide occurring in an 11-square-mile area (nominally the size of a lease block) (updated Fig. 78 from OTRC 2007)

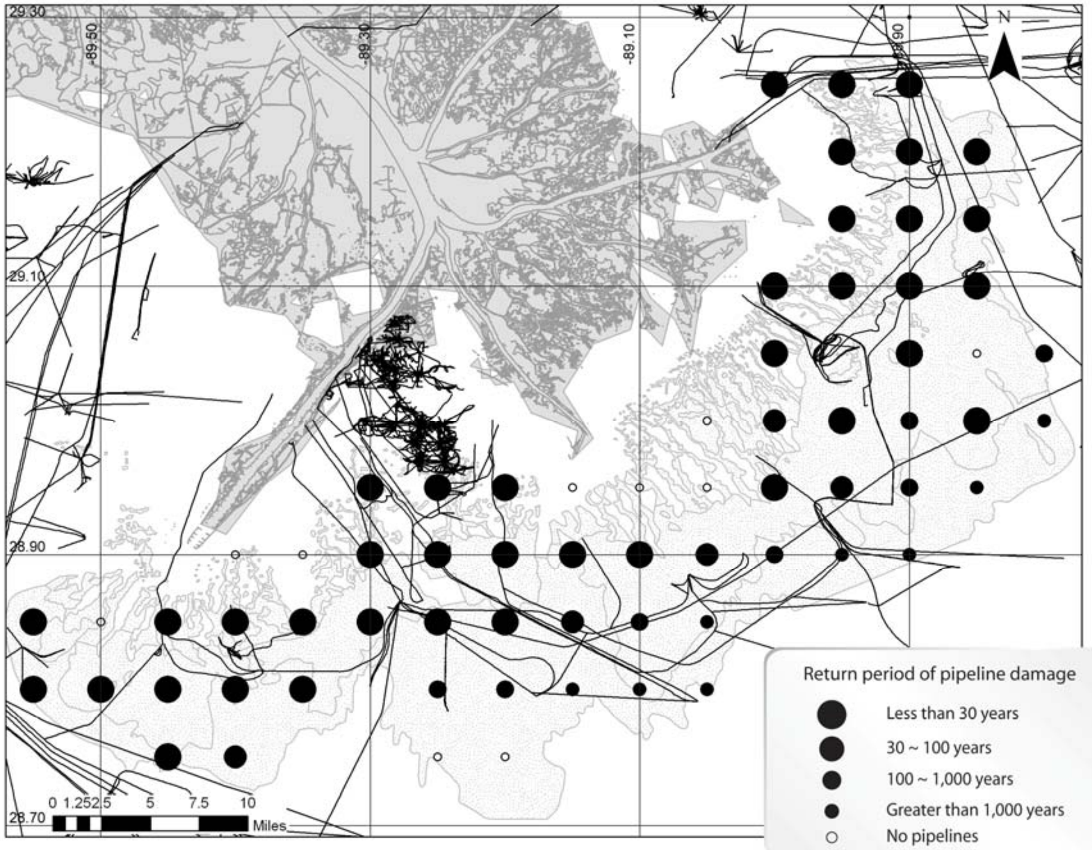

Figure 18: Return periods for mudslides impacting existing pipelines (updated Fig. 79 from OTRC 2007)

IV. CONCLUSION

The wave hazard used to assess the risk for mudslides in the Mississippi Delta (OTRC 2007) has been improved to account for the possibility of longer-period, smaller waves causing mudslides. This updated approach accounts for the possibility of an Ivan-like case, where the eye of the hurricane was 90 miles to the east of the Delta and the waves in the Delta, although smaller than those near the eye, had long periods like the largest waves near the eye. The effect of the updated approach is to reduce the return period for a mudslide occurring at a particular location in the Delta; the reduction in return period is less than 10 percent for return periods up to 30 years, at most 30 percent for return periods up to 100 years, and at most 50 percent for return periods greater than 100 years. The maps showing the risk of mudslides in the Delta published in the final project report (OTRC 2007) have been revised in this Addendum to reflect the updated model for the wave hazard.

REFERENCE

OTRC (2007), Mudslides During Hurricane Ivan and an Assessment of the Potential for Future Mudslides in the Gulf of Mexico," Final Project Report, Offshore Technology Research Center, Prepared by Nodine, M. C., Wright, S. G., Gilbert, R. B., Ward, E. G. and Cheon, J. Y., Prepared for Minerals Management Service, Herndon, Virginia.