A GUIDE TO UNDERSTANDING INLET-INDUCED EROSION PATTERNS : EXPECTATIONS FROM NUMERICAL MODELING

A Research Paper

By

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Notes Added To The WEB Copy , 1/17/97, by E.F. :

1) This paper was produced as a work related research paper in 1994. It was intended to be a guide for staff people in understanding some types of coastal processes. It was not submitted to a journal or conference proceeding primarily because of its' length. However, a prior and shorter version was published as noted in newly added Reference 3 . Also Reference 1 has been revised to note its' publication after the 1994 date. Some further research has since been carried out ; see the note in Case 2 in particular.

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3) The opinions expressed in this paper are those of the author and do not necessarily reflect those of the FDEP.

4) The figures and appendix for the ASCII text version have been enclosed in the zipped total file as separate bitmap files, which can be viewed and printed via many software products, e.g., Wordperfect, Adobe, etc. The intent was to produce a document for general informational purposes which can be read independent of any particular software. There is also an ASCII text list of figures.

INTRODUCTION

This paper is concerned with exploring via numerical modeling the types of erosion patterns that should be found on the downdrift side of inlets. Two cornerstones of coastal engineering are : (1) the essential form of the longshore sand transport equation, and (2) the need to account for all the sand in a system. The model in this study simply makes calculations using those two axioms. A base case and several variations intended to show the effects of frequently used erosion control measures are presented. Additional cases are presented to further examine or clarify some of the major issues raised by the results. It is intended to give the reader some firmly grounded theoretical basis for observing and understanding what is actually seen on the coast in similar inlet-induced erosion situations. The suggestion is to first see if an inlet has an erosional history consistent with that expected from basic longshore sand transport theory, rather than trying to generate new and sometimes observationally inconsistent theories about each inlet. Reference 1 compares the theory-based results with observed historical changes at many Florida inlets. The author contends that there are at least 33 inlets in Florida that exhibit essentially the same erosion pattern as determined here from theory. These appear to differ from the general case only in the details of the local conditions. The Department of Environmental Protection (DEP, formerly Dept. of Natural Resources - DNR) historic shoreline data base is described in Reference 2, which also includes an example comparison of an actual inlet with the theoretical pattern developed in detail in this paper.

A one-line, two-season, longshore numerical model was used to show the expected theoretical erosion patterns with conditions generally approximating those common, for example, on the east coast of Florida: a north-south shoreline with predominant wave energy out of the northeast. The processes described are not, however, limited to the Florida east coast, or only to Florida. Any sandy shoreline with similar conditions should react in the same way. Unless otherwise noted, a complete littoral barrier is assumed as the model's north (left side) boundary, simulating an inlet with jetties and no significant bypassing. The boundary condition could also represent an ebb shoal that acts as a complete littoral sink. The model employed is a finite difference model as defined in the Appendix section, which may be used for both calibrated and generalized cases. The model is based on the physics of longshore sand movement caused by waves, as expressed by a basic form of the sand transport equation. Sand volume is conserved. The profile cross section is approximated by a parallelogram. In calibrated usage, the depth of the parallelogram would be set such that the cross-sectional area change per unit of shoreline retreat would be equivalent to that measured in actual profiles. The mean high water (mhw) contour is tracked in the modeling, although it could be any other elevation contour on the profile which acts in parallel. Coastal engineering literature contains many similar models, any of which should be capable of producing the same results discussed in this paper.

Unless otherwise indicated, the common set of conditions used in these simulations is the following:

- x interval = 200 feet
- time interval = 43200 sec = 12 hours
- depth of parallelogram cross-section = 12 feet
- season 1 or "winter" = 90 days of waves with breaking height 2.0 feet and attack angle of 3 degrees
- season 2 or "summer" = 30 days of waves with breaking height 1.0 foot and attack angle of 3 degrees.

In order to understand something it makes sense to start with the simplest conditions and then add complexity. There are twelve (12) cases, each of which builds on prior results. There are forty (40) figures, all of which are to be found after the last page of text, following the References.

CASE 1: 60 YEAR BASE CASE

A plan view of the base case is shown in Figure 1A. The year zero shoreline is represented by the horizontal line at y=0 . The eroding shorelines at 10 year intervals are plotted. Note the characteristic v-shaped pattern in the plan view. Another characteristic erosion pattern results when shoreline location is plotted versus time relative to selected reference points (similar to DEP reference monuments along the coast), as shown in Figure 1B. Reference point locations are selected at 5000 ft intervals along the X axis, and shoreline locations are measured along the east-west bearings shown as dashed lines in Figure 1A. In the shoreline distance versus time plots, as given in Figure 1B, a downward sloping line indicates erosion. The steeper the slope, the higher the erosion at the reference location.

As can be seen in the two figures, the erosion pattern is progressive and non-linear: the areas closest to the inlet erode first and fastest; those further from the inlet do not immediately erode but eventually are caught in the erosion pattern. The erosion pattern will progress southward alongshore until another boundary and its' effects are encountered. The non-linearity of the pattern in space (the x,y coordinate system) and time is an important observation and may be expected to be found in the historical records of shoreline change south of an inlet with jetties or an ebb shoal sink.

The shape of the theoretical erosion curves will be discussed in more detail in later sections. Specifically the flattening of the slope of the distance vs time curves, the effects of changing certain variables, and the longshore extent of the erosion pattern will be addressed.

At this juncture a discussion concerning the use of simplified conditions is warranted. In reality there are usually several complicating factors to consider on the downdrift side of an inlet. To name a few : (1) the downdrift side jetty may not be sandtight or not very long, and may be a sink for updrift sand transport; (2) there may be a counter-clockwise current in the lee of that jetty, caused by the jetty configuration and the jet flow of the ebb tide; (3) there may be a bypassing shoal acting as a sand supply source for downdrift beaches; (4) there may be a sand bypassing facility or renourishment project(s); (5) there may be refraction and diffraction of the wave pattern caused by the jetties and the shoals; (6) there may be nearshore reefs or rock exposures in the area; and (7) there may be coastal armoring structures affecting the erosion pattern. The first two of these items may be expected to increase the erosion by inducing greater sand losses. Items 3 and 4 should act to decrease the erosion by increasing the sand supply. Items 5 and 6 can modify the wave climate. Items 6 and 7 can involve the addition of more littoral barriers to the problem. However, all of these factors should only modify the basic pattern.

If it can be observed in the field or in aerial photographs that significant wave activity occurs in the immediate downdrift zone, then the sand transport equation should still be the controlling factor influencing shoreline orientation and shape.

To allay some immediate concerns that the reader may have as to the adequacy of the initial simplified conditions, the effects of inserting a wave refraction pattern next to the jetty, of doubling season 2 wave energy, and of incurring a 30% volumetric loss through (or around) the jetty are presented in Figures 1C and 1D. As can be seen in the figures, the effects on the base case are minimal. Of course, more radical effects can be achieved by more radical changes in the conditions, but within reasonable limits these should still produce recognizable variations on the basic pattern. If the conditions are changed too much, then the pattern observed will not be what's under study here, i.e. , that caused by dominant wave attack from one direction.

CASE 2: RENOURISHMENT NEAR THE INLET

Renourishment projects are frequently used to reduce erosion problems in inlet-affected areas. In this case, the theoretical effects of a renourishment project which occurs immediately south of the inlet in year 20 of the base case are examined. The width of the fill is 150 feet and the project extends for almost 10,000 feet. The fill material is assumed to be the same as the natural sand. The model is run for 30 years, from base case year 20 to year 50.

Figures 2A and 2B show the model results. The shorelines for years 20, 25, and 50 are shown in Figure 2A. The fill spreads southward over time, providing a source of sand supply for downdrift beaches. The effect of the fill project as seen in the distance vs time plots of Figure 2B may be described as resetting the erosion clock: the original erosion pattern is interrupted and delayed by the fill, but eventually is reestablished at essentially the same rates, in this case about 15 years later. The effect of repeating the fill projects would be to delay the erosion pattern for as long as the repeated fillings occur. Once the filling stops, the original erosion pattern can be expected to begin again unless the basic controlling factors of wave climate and sand supply are changed.

Note that this case is for an equal width fill. Renourishments are not necessarily of equal width throughout, and can contain sections of over-fill or greater width. The over-filled areas will generally erode faster because they represent an even greater discontinuity on the curve of the shoreline.

NOTE ADDED 1/17/97 TO CASE 2 :

Intervention with fill in this case occurred fairly early in the erosion pattern, year 20. There have been many real cases where intervention with filling did not start until much later in the pattern. In such a case the filling next to the inlet will halt erosion nearby but not necessarily halt the rest of the downdrift erosion pattern which has already spread much further away. In some situations the erosion of the fill can be relatively slow, while beaches at the leading edge and center of the erosion pattern continue to erode strongly. This is a complicated situation that hopefully will be addressed via a future case study.

CASE 3: EFFECTS OF A NATURAL HEADLAND OR SHORELINE ARMORING

Many areas of Florida's coast are influenced by nearshore reefs and rock exposures. In many cases, the historic record strongly correlates greater mhw stability but also greater storm vulnerability with areas having these geologic features. Observations of the wave patterns in aerial photographs of reef and rock-influenced areas suggest that such features can cause wave refraction, diffraction, and breaking. They can also act similar to man-made armoring. It is noted that high water levels during storms can allow waves to cut into the beach normally sheltered by reefs or rock exposures, thus accounting for the high vulnerability of buildings built too far seaward on natural headlands. There are also many coastal areas of Florida with extensive sections of man-made armoring influencing shoreline erosion.

In this model case, the same conditions are held as in the base case except that a certain area of the beach between x = 20,000 and x = 24,000 feet is held as if it were rock and non-eroding. The cause could be a shallow nearshore reef, or a rock exposure along the mhw line, or a rock revetment or seawall along the mhw line. It is noted that in observations of rock revetments and seawalls in highly eroding areas, eventual destruction by storms is far more likely than the structures being massive and deep enough to hold the shoreline indefinitely.

The boundary conditions representing the headland in this case are greatly simplified. Essentially the headland is considered to be a groin, and no sand is allowed to accumulate along the seaward face of the feature. The more accurate conditions allowing for sand to accumulate on and move across a surface are complicated, and really require their own report. The simplification is deemed adequate for the purpose of this study because the updrift and downdrift effects will not be that greatly modified by the more complicated conditions that actually exist across the headland.

The model results are shown in Figures 3A and 3B. In the former figure the shorelines for every tenth year are shown. The flat surface and square corners of the headland are merely part of the simplified illustration. In a natural feature the headland would likely be rounded. In both figures the effect on the erosion pattern is seen to be a reduction in the erosion rates updrift of the headland, and increased erosion downdrift of the headland. Since the erosion pattern is progressive, one indicator of the extent of an inlet's present erosion influence would be to observe if a characteristic erosion pocket has been carved out downdrift of such a feature.

CASE 4 : RENOURISHMENT AWAY FROM THE INLET

In this case, the same conditions are held as in the base case except that a renourishment occurs between 10,000 and 18,000 feet south of the inlet in year 30 of the base case. The width of the fill is 150 feet. This is, of course, a similar case to Case 2, but the situation is common and important enough to warrant an investigation of the expected effects.

The shorelines for years 30, 35, and 60 are shown in the plan view of Figure 4A. There is spreading of the fill to both sides via seasonal wave energy, but predominantly to the south. As can be seen in Figure 4B, the erosion pattern is delayed and then reestablished. The effect of continually repeating the renourishments would be, as in Case 2, to reset and delay the erosion pattern as long as the fill projects continue. As in Case 2, it would be a situation of maintaining a stalemate with the forces causing the erosion.

CASE 5 : EFFECTS OF A GROINFIELD NEXT TO THE INLET

The model input conditions for this case have been changed. A smaller X distance interval was needed because the groin effects being examined are relatively small scale compared to the total area affected. A smaller time interval was required to maintain model stability. A lesser season 2, or "summer" season, was chosen because the shoreline orientation inbetween the groins was found to be very sensitive to even small seasonal wave direction changes. The model program happens to be set up to output shoreline positions at regular time intervals after season 2 has been completed. In order to show a shoreline orientation between the groins as lined up to face the predominant northeast wave energy, it was desirable to minimize season 2 effects. There was correspondingly no need to have a large season 1, which would only scale up the effects. The attacking wave angles were also reduced for the same reasons.

The model input conditions are now the following:

- x interval = 50 feet
- time interval = 3600 sec = 1 hour
- depth of parallelogram cross-section = 12 feet
- season 1 or "winter" = 30 days of waves with breaking height 2.0 feet and attack angle of 2 degrees
- season 2 or "summer" = 1 day of waves with breaking height 0.5 foot and attack angle of 2 degrees.

Three groins centered at respective x distances of 225, 475, and 725 feet south of the inlet were set up in the model. The mhw was allowed to reach the seaward tip of a groin before bypassing sand southward (a lesser distance could have been chosen but the choice is unimportant for illustration purposes). The seaward extent of the groins was set at the y = 0 initial shoreline position. For simplification, the width of the groin structures was considered to be nearly the same as the x interval of 50 ft.

In Figure 5A the base case for the groinfield is shown. No sand transport into the model area from the north is allowed. The shorelines at years 0 through 6 are shown. The erosion pattern is essentially the same as that of Case 1 except that it has been shifted southward by stabelizing the shoreline immediately adjacent to the inlet. Note that the shoreline within the groinfield is almost immediately (by the end of year 1) fixed. The fix is volumetric since the shoreline will rapidly shift orientation seasonally within the groinfield.

In Figure 5B the effects can be seen of allowing various constant levels of point source transport Q(in) into the model at the north boundary during season 1, simulating a bypassing plant discharge pipe. The quantities are per annum. Note that the groins fill up to greater fixed volumes at greater levels of Q(in), and the downdrift erosion is less with greater values of Q(in). These results suggest that a groinfield can be expected to maintain a "filled" configuration relative to the amount of sand supply it receives. Although it should be possible to fill or empty a simple groinfield according to how much sand is pumped in, a shifted erosional zone would still occur.

A further comparison is made in Figure 5C where the situation with and without a groinfield is shown. An amount of Q(in), again in units of cubic yards per year, which almost completely fills in the groinfield is established. Years 0, 1, and 6 are shown for the groin and no groin situations with the non-zero Q(in). The zero Q(in) groin case is also included. It can clearly be seen that stabelizing one section of eroding beach can be expected to increase the erosion in downdrift areas. A shifted erosion pattern could be considered an undesirable tradeoff in many real situations.

CASE 6 : EFFECTS OF A GROINFIELD AWAY FROM THE INLET

The model input conditions are the same as in Case 5 with Q(in) set to zero. The same groins as in Case 5 have been placed to the south, centered at 4975, 5225 and 5475 feet, respectively. The model was run for 20 years to allow time for the erosion pattern to reach and significantly react with the groinfield.

Given the previous results of the headland Case 3, the expected shoreline reaction should be that the erosion on the north (updrift) side of the groinfield would be reduced, and the erosion on the south (downdrift) side increased. Also, based on the results of the groinfield Case 5, since Q(in) into the groinfield is not fixed but is reducing over time, the groinfield should empty over time. However, the emptying of the groinfield should slow down to very small amounts as Q(in) comes closer to being a constant.

As can be seen in Figure 6A and the enlargement of Figure 6B, the expectations based on previous cases do indeed occur in the model results. This may be why groinfields in eroding areas have historically been abandoned over time : they cannot be easily kept filled, and they have downdrift effects. Since the groins become more exposed over time, the need for repairs due to storm damage also likely increases over time.

CASE 7 : POINT SOURCE BYPASSING VS RENOURISHMENT

The same conditions are held as in the base case. The effect of point source bypassing can be seen in Figure 7A. At the end of year 20 of the base case a point source supply was activated at the north (left) boundary for 30 additional years. The amount of Q(in) per year was set equal to the fill amount of Case 2 divided by the number of years it took for the shoreline to revert back to approximate pre-fill conditions, i.e. , 15 years. The effect can be seen in the Figure 7A shorelines for years 30 and 50 as producing a significantly flatter erosion pattern, with more sand accumulated next to the north jetty boundary. The year 30 and 50 shorelines in this figure may be compared with the year 30 and 50 shorelines of Figure 1A of the base case.

Figure 7B shows a comparison between the shorelines 15 years after the renourishment placement of Case 2 versus 15 years after the point source sand supply was started. Recall that year 20 of the base case was the initial shoreline for both alternatives. After 15 years the renourished shoreline closely resembles the initial year 20 shoreline. However, after 15 years of point source supply the shoreline has a flatter curvature, with less erosion next to the jetty and more erosion downdrift.

Figure 7C shows the differences on the distance versus time plots. A significantly different erosion pattern is evident. Note that this figure shows the effect of only one renourishment, whereas the point source supply is continuous over years 20 through 50. Therefore the comparison is only equal over years 20 through 35, when the Q(in) total values are approximately equal. Multiple renourishments would produce an up and down series of fill and erosion lines. Note also that the amount of point source supply will have an effect on the shoreline response curves.

There can obviously be a difference in effects between the fill and point source alternatives which should probably be considered when deciding how to best manage inlet erosion effects. For example, if there are threatened structures in the immediate downdrift zone, would it be better to maintain an existing sharper shoreline orientation with repeated renourishments, or to establish a flatter shoreline orientation with a point source bypassing system ? Either could be the more desirable solution depending on the circumstances.

CASE 8 : EFFECTS OF EBB SHOAL BYPASSING

Some inlets can be observed to have ebb shoal systems which bypass sand from the updrift to the downdrift shorelines, with the sand coming ashore within some observable zone. This can be simulated by adding small amounts of shoreline width uniformly over time within a selected zone during season 1 of the model. The selected zone in this case will be 4800 to 5400 feet south of the inlet. The total shoreline width added per year is 50 feet. The additions will commence after the 10th year, simulating the need to build the bypassing shoal for some period of time after the inlet is opened. Otherwise the conditions are the same as the base case.

The plan view effects versus the base case are illustrated in Figure 8A, and further in Figure 8B where the amount of shoaling is doubled. Essentially a bend or bulge in the erosion curve is created at the shoal merging zone and the amount of erosion is reduced by the addition of the sand supply. The effect on the distance versus time curves of the initial (not doubled) shoaling case is shown in Figure 8C. The rates and amounts of erosion are obviously reduced depending on the amount of bypassed sand. An effective bypassing shoal can be a valuable asset in minimizing downdrift erosion.

CASE 9 : WHEN DOES THE EROSION SLOW DOWN ? - BOUNDING EROSION WITH A HEADLAND OR GROIN

The reader may recall that in Cases 3 (headland) and 6 (groins away) the area between the structures and the jetty became a compartment in which the erosion amount and rate was reduced. In order to explore this effect in greater detail a similar headland as in Case 3 was inserted closer to the inlet, between x = 10000 and 13000 feet. The model was run for the base case conditions, then again with the season 1 wave height increased to 2.5 feet, and once more with the season 1 attack angle increased to 6 degrees.

Figure 9A shows the effects in plan view. Increasing the wave height slightly increases the amount of erosion in the compartment, but not nearly as much as that resulting from an increase in the attack angle. This is because the shoreline in the compartment is trying to front the attacking waves. No matter what size the compartment, the erosion of the shoreline to face the attacking waves is the ultimate result of applying the equations in the model. The base case erosion pattern is simply the beginning stage of this process in a much longer compartment. This topic will be explored further in the next two sections.

Figure 9B shows in distance versus time plots that the nearby headland causes the slope of the erosion curve at the x = 5000 ft reference point in the compartment to flatten out to a closer to zero rate by the 60th year. The wave height increase causes this to occur more rapidly. The original base case with no headland can be seen as far from flattening out to a near zero rate.

Figure 9C shows in distance versus time plots that the increase in wave attack angle causes much greater erosion and is less flattened out by the 60th year at the same reference point.

CASE 10 : WHEN DOES THE EROSION SLOW DOWN ? - LOOKING AT MUCH LONGER TIME PERIODS

From the previous case it was realized that the distance between boundaries is a primary control on when the erosion in a compartment slows down. A compartment can be the 100 or so feet between groins, or maybe 50 miles between inlets. It was also seen that higher predominant wave height (closely related to wave energy) causes the shoreline reaction to occur faster, although the amount of erosion appeared more a function of the attack angle. Wave height and attack angle are the two most important factors in the longshore sand transport equation (see the Appendix). Increasing either must increase the erosion. The nearby headland boundary must have greatly limited the wave height influence.

Looking at much longer time periods will clarify the effects of wave height and attack angle, and will add more information about if and when the erosion rates can be expected to lessen when there is no south (right side) boundary influence.

In Figure 10A the effects of three different season 1 wave heights over 120 years is examined. The model conditions are the following :

- x interval = 200 feet
- time interval = 43200 sec = 12 hours

- depth of parallelogram cross-section = 14 feet
- season 1 or "winter" = 60 days of waves with breaking heights 1, 1.5, and 2 feet, and attack angle of 20 degrees
- season 2 or "summer" = 15 days of waves with breaking height 1 foot and attack angle of 3 degrees.

The above changes (other than wave height) were not absolutely necessary but did help limit the number of points and hense model run time, and allowed for clearer illustration of the effects.

Figure 10A shows that a higher wave height definitely increases the amount of erosion in an unbounded right side situation.

Figure 10B shows in distance versus time plots that over longer periods of time in an unbounded situation the erosion rate becomes a very slowly changing value but does not show a strong tendency to zero out. The smaller the predominant wave height, the lower the rate of erosion and the lesser amount of erosion in equal time periods.

The effects of three different season 1 wave attack angles over a 120 year time period are shown in plan view in Figure 10C. The season 1 wave height is kept at 2 feet and the attack angle is increased from 5 to 10 to 20 degrees. This increases the erosion in a manner very similar to the wave height effect. Also shown is the eroded shoreline at 300 years for the 5 degree situation. The 300 year shoreline is seen to be a continuation of the same characteristic pattern shown for 120 years. In Figure 10E the time scale is extended to show that even with the lesser erosion resulting from the 5 degree wave attack angle, the rate has not flattened out to a near zero value even over 300 years.

A conclusion that can be reached from these results is that the downdrift erosion problem is limited primarily by the boundary conditions in a system. This will be explored further in the next case section.

To finish the examination of longer term effects, Figure 10F shows in plan view the effects over 120 years of reducing the beach cross section by changing the depth from 14 to 12 feet. Also shown in the figure is the effect of increasing the number of days of season 2 waves from 15 to 50. The cross section reduction results in greater shoreline recession since the amount of attacking wave energy was not reduced.

The increase in season 2 duration results in a relatively small reduction in erosion, confirming and expanding on the 60 year test of Case 1.

CASE 11 : THE LARGER PICTURE - BOTH END BOUNDARIES, SHORELINE ORIENTATION, AND ZONES WITH DIFFERENT WAVE HEIGHTS

In all the cases up to this point, only one end (the eroding end) of a coastal system was examined. A greater level of understanding may be obtained by looking at a complete system. For example, a system bounded at both ends by an inlet with jetties, each representing a complete littoral barrier, is shown in Figure 11A. It can be seen that the shoreline change pattern on one side of the dotted mid-point line (at x = 50000 ft) is a mirror image inverse of the other. That is, the erosion on the left side is exactly equal to the accretion on the right side. The conditions are those of the base case. Note that at 120 years the erosion pattern on the left is about to interact with the accretion pattern on the right.

Taking this approach a few steps further, in Figure 11B the effects are shown of changing the left boundary to a point source of supply (Q(in) = 32878 cu.yds./yr.). The evolving shoreline change pattern is quite different, as may have been expected from Case 7 results. Note that there is interaction of the erosion and accretion patterns well left of the mid-point of the system. The 120 year shoreline shape is reminiscent of the regional shoreline shape of the east coast of Florida from the St. Johns / Flagler county line to Cape Canaveral. The Cape could well be considered a very seaward extended boundary condition similar to that in the model. The northern boundary condition could be considered the equivalent of a point source of supply. Of course, that region has been evolving for thousands of years.

Another model case can be generated by causing the right side boundary to be a terminal groin or jetty with limited length. Such a structure allows sand to leave the system across that boundary. The left side boundary is set to be a complete littoral barrier. As can be seen in Figure 11C, again there is an intersection and interaction of the erosion and accretion patterns, this time to the right of the mid-point. In some actual coastal systems there are probably interacting end boundary effects.

In all the cases up to this point there has been an initially straight (y = 0) shoreline, simulating a pre-inlet straight shoreline. In some Florida locations there is a distinct change in shoreline orientation within an inlet to inlet system. In the modeled situation shown in Figure 11D, the right side of a system is separated from the left by a non-eroding headland, but the right side orientation presents a greater wave attack angle with season 1 waves. This results in increased erosion on the right side of the headland, although there is no interaction yet with the inlet induced erosion pattern. If the headland is allowed to be eroding sand, it represents a discontinuity in shoreline curvature that is eroded to a smoother curvature, as shown in Figure 11E. Many natural headlands are likely to be very slowly eroding, combining features of both erosion patterns. Shoreline orientation can be a necessary consideration in actual erosion cases.

In certain areas within a coastal system there can be greater or lesser wave energy. For example, a gap in a reef that runs throughout a region could result in a zone of higher wave energy. The results of modeling a zone with 10% increased energy are shown in Figure 11F. A zone of 10% lower wave energy is also modeled, with the results shown in

Figure 11G. In both figures, going from a higher to a lower wave energy zone in a system will cause an accumulation of sand in the area between the two zones. Going from a lower to a higher wave energy zone will cause an erosion of sand in the transition area. It is noted that features resembling structure-based headlands can be caused by wave energy differences along a shoreline.

CASE 12 : LINEARLY SUPERIMPOSING EROSION EFFECTS

Real inlet-induced erosion situations are likely to include several of the effects shown in the previous cases. It would therefore be useful to know how multiple effects interact. In the modeling results of Figures 12A, 12B, and 12C, it is shown for an inlet-induced erosion situation with structural, wave energy (10% increase), and fill effects, respectively, that the effects are linearly additive. For example, Figure 12A(i) plus (ii) equals (iii), graphically and mathematically.

Erosional patterns can be superimposed to obtain a net (interacting) effect. Useful analogies cound be drawn with the additive properties of tidal wave components and electrical signals. Shoreline erosion patterns are waveforms as well. This result has many implications and can potentially be a great help in understanding real coastal systems.

For instance, let's say there is an inlet-induced erosion pattern in a large coastal system that includes a series of headland features. Suppose this erosion pattern spreads for many years a considerable distance downdrift, past a few of the headlands. Then at the updrift inlet end a renourishment program is initiated. Repeated renourishments occur south of the inlet, not necessarily at equal time intervals or in equal amounts. By knowing that the effects of each erosion pattern can be superimposed, it is evident that there will be a moving, leading wave of erosion from the original pattern, which won't stop until it interacts with the system end boundary. There will also be waves of sand deficit and supply moving through the series of pocket beaches, depending on and spaced by the timing and amounts of the fill events.

Such a system is clearly not simple, but it can be understood from a overall perspective. With enough monitoring, it may be possible to model an actual, similarly complex system and achieve a reasonable level of predictability. Allowance would have to be made, of course, for yearly variations in wave climate.

Caution is advised in applying the linear superimposition principle. Only straight-line, simple systems have been tested here. It would be wise to carefully consider and test how it can be applied in modeling a real system.

COMMENTS

In recent years there has been a significant amount of controversy and confusion surrounding inlet issues. The author saw a need to establish and present a firm theoretical basis for examining inlet-induced shoreline erosion problems. The base case and variations presented herein should prove helpful in examining real problems because the physics involved in the modeling is essentially correct and waves are obviously a controlling influence. It is suggested that this back-to-basics approach will clarify the observed shoreline changes at a great many inlets in Florida where the conditions are similar to those presented here.

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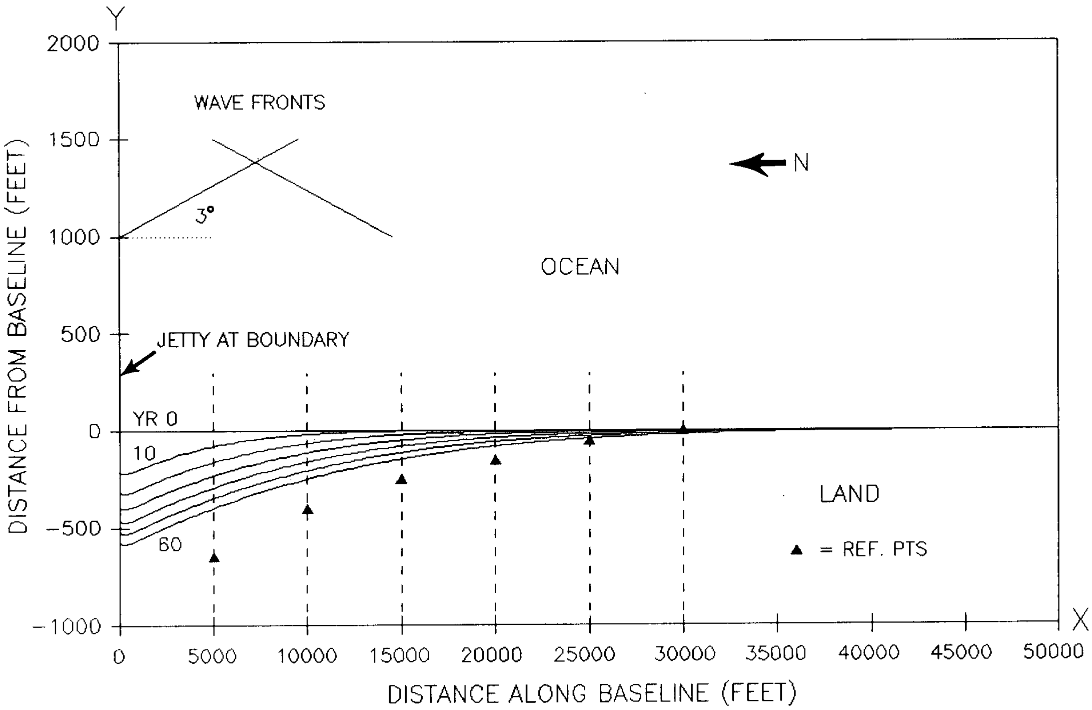


FIG. 1A — PLAN VIEW, BASE CASE, EROSION SOUTH OF INLET

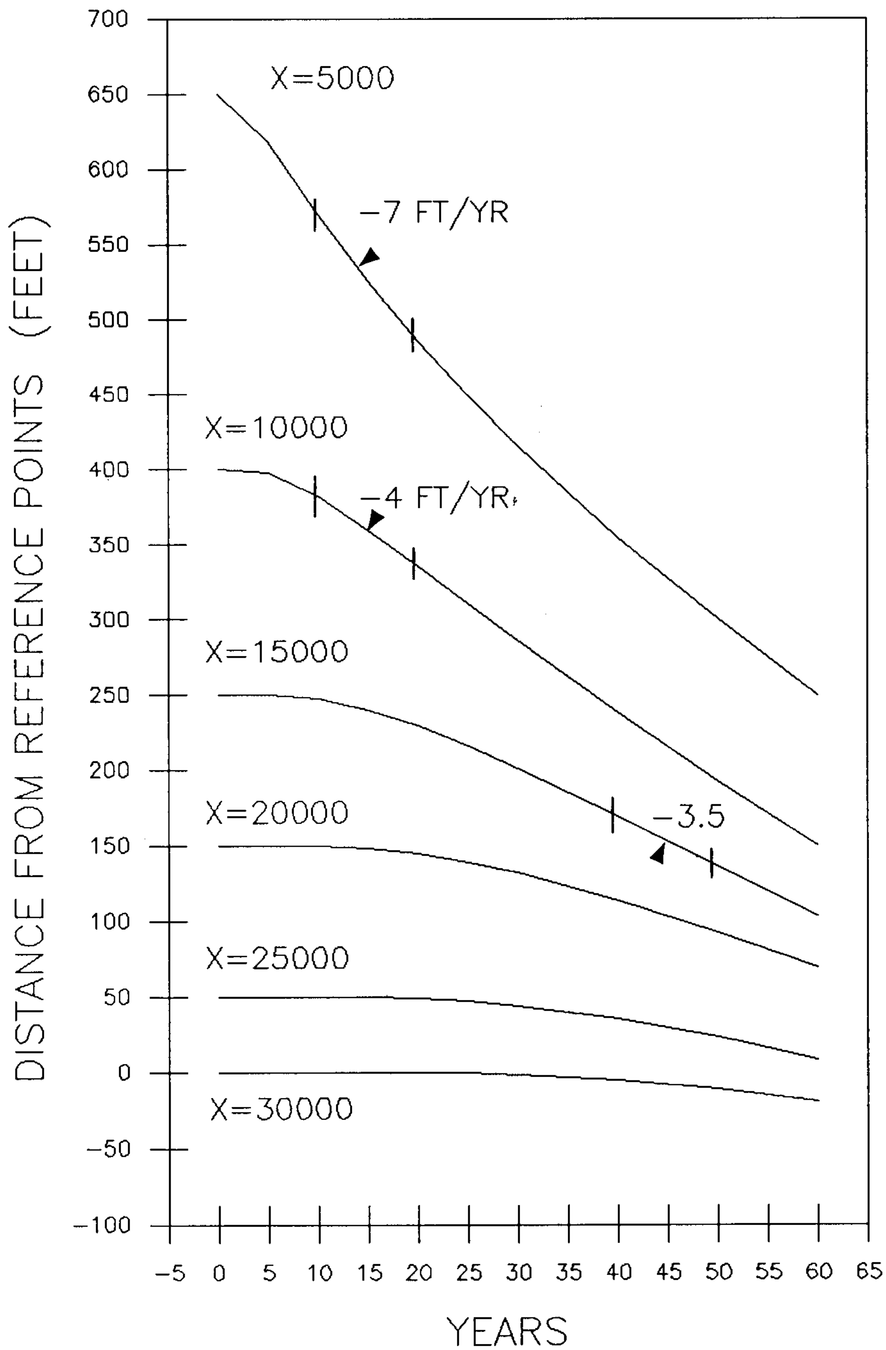


FIG. 1B – BASE CASE, DIST. VS. TIME PLOTS

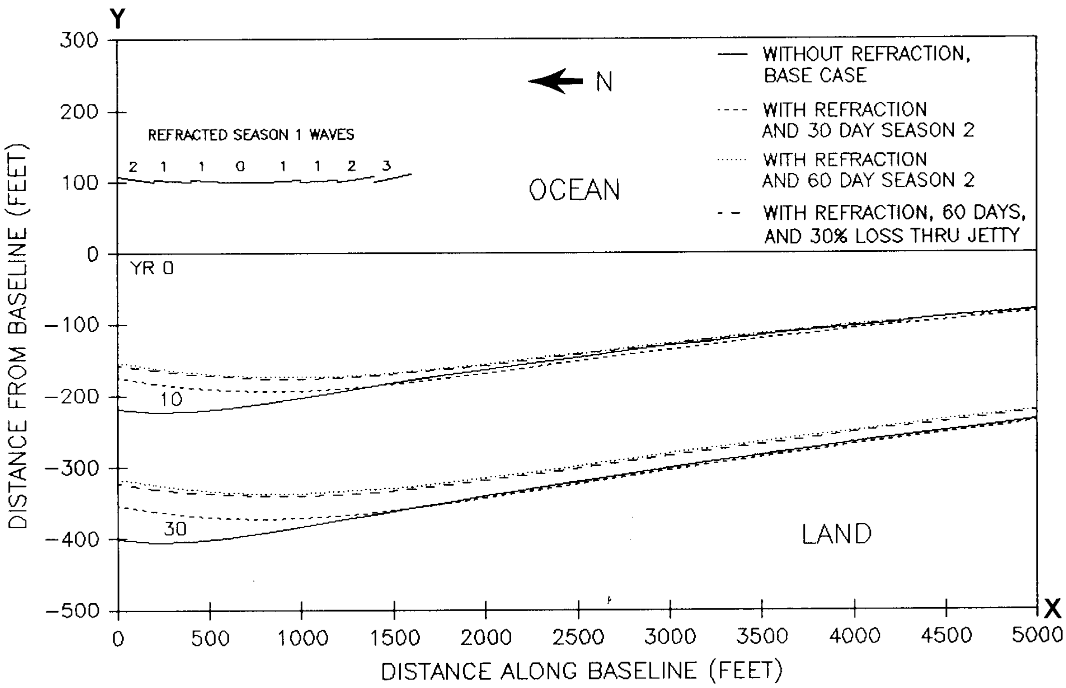


FIG. 1C – PLAN VIEW, CLOSE TO INLET: REFRACTION, SEASON 2, AND POROUS JETTY EFFECTS

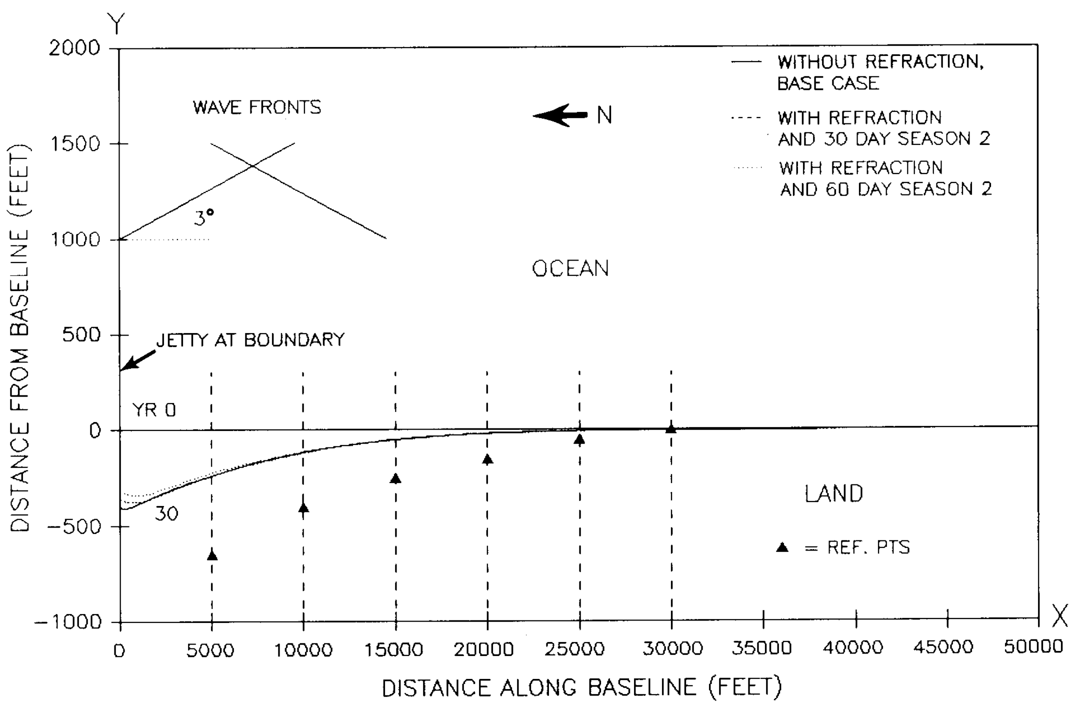


FIG. 1D – PLAN VIEW: REFRACTION AND SEASON 2 LARGE SCALE EFFECTS

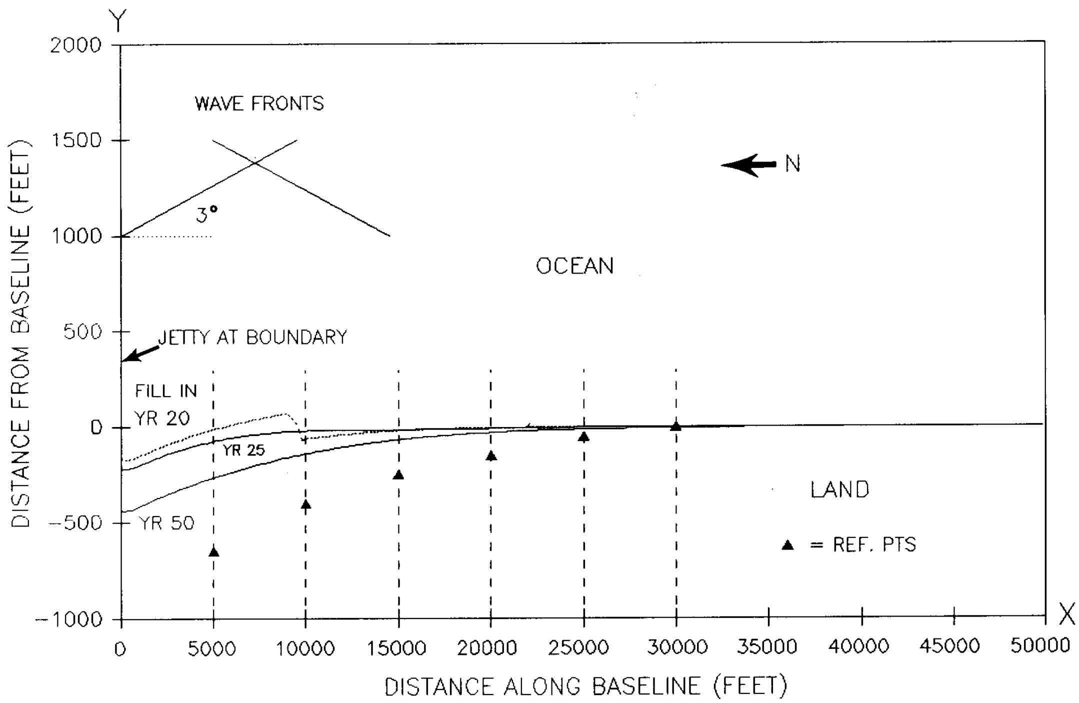


FIG. 2A — PLAN VIEW, FILL NEAR INLET CASE

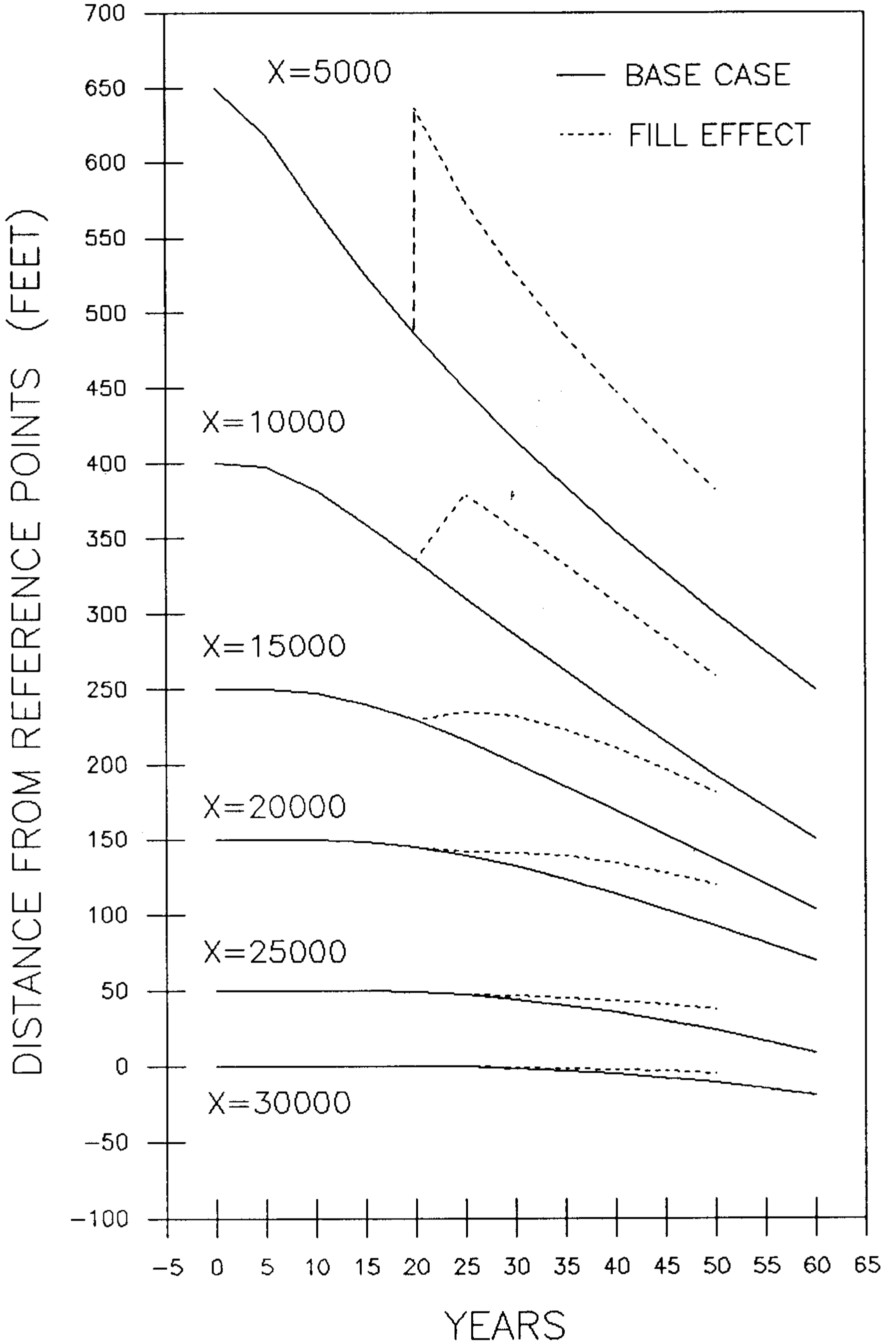


FIG. 2B – FILL CASE, DIST. VS. TIME PLOTS

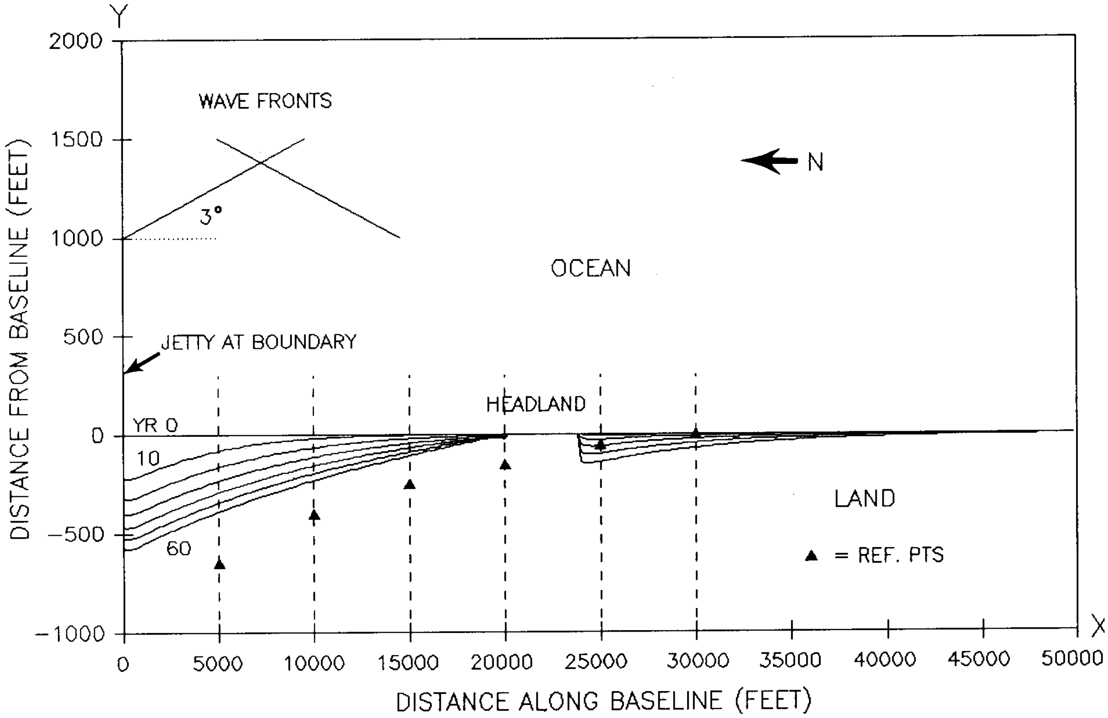


FIG. 3A — PLAN VIEW, HEADLAND CASE

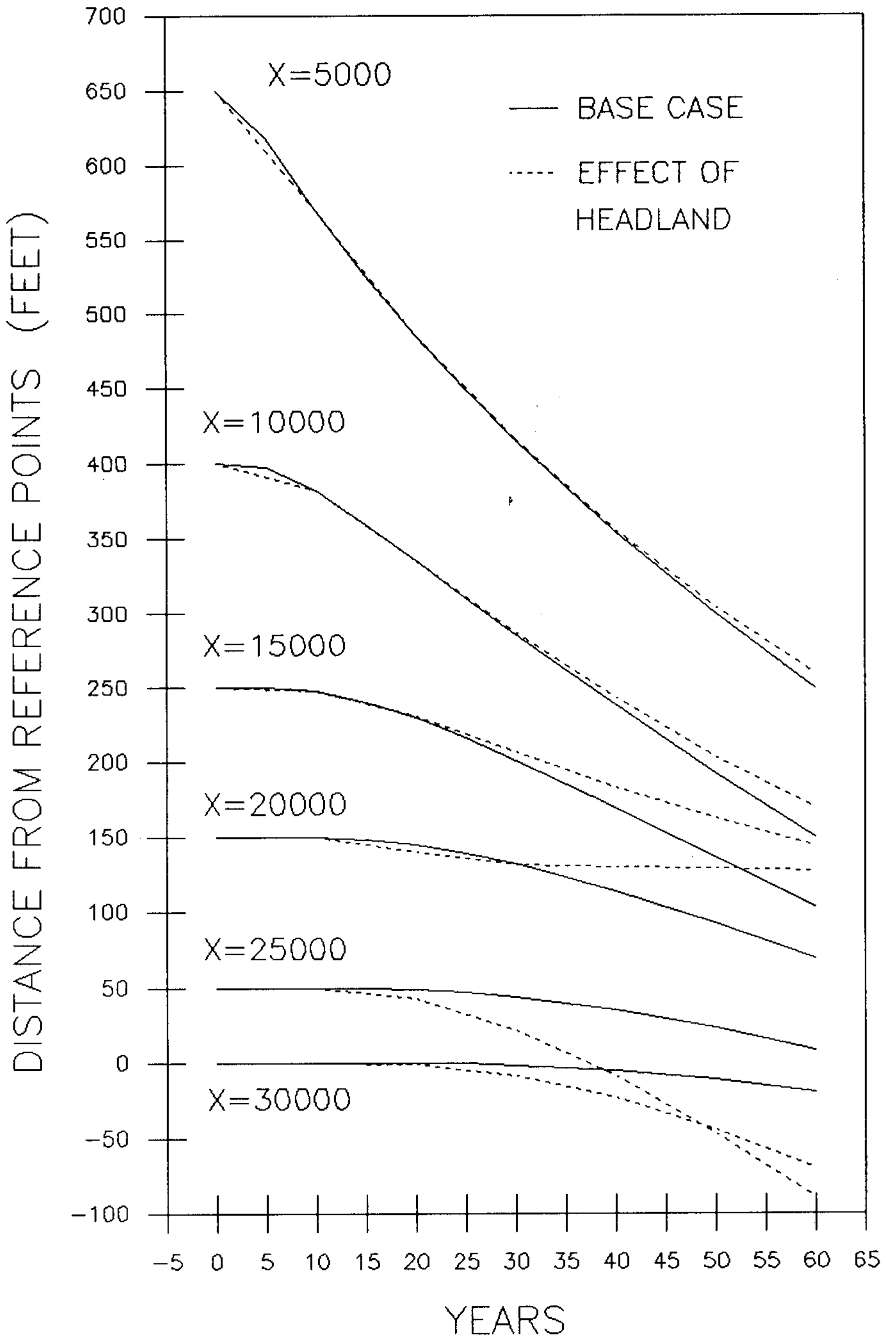


FIG. 3B – HEADLAND CASE, DIST. VS. TIME PLOTS

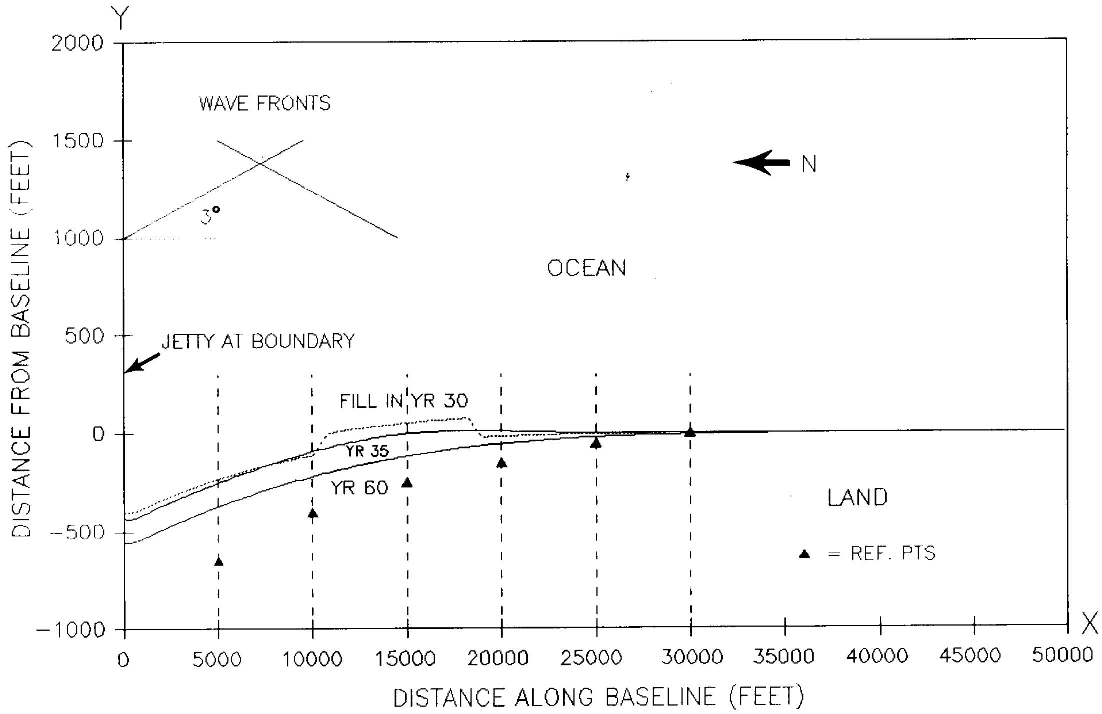


FIG. 4A – PLAN VIEW, FILL AWAY FROM INLET CASE

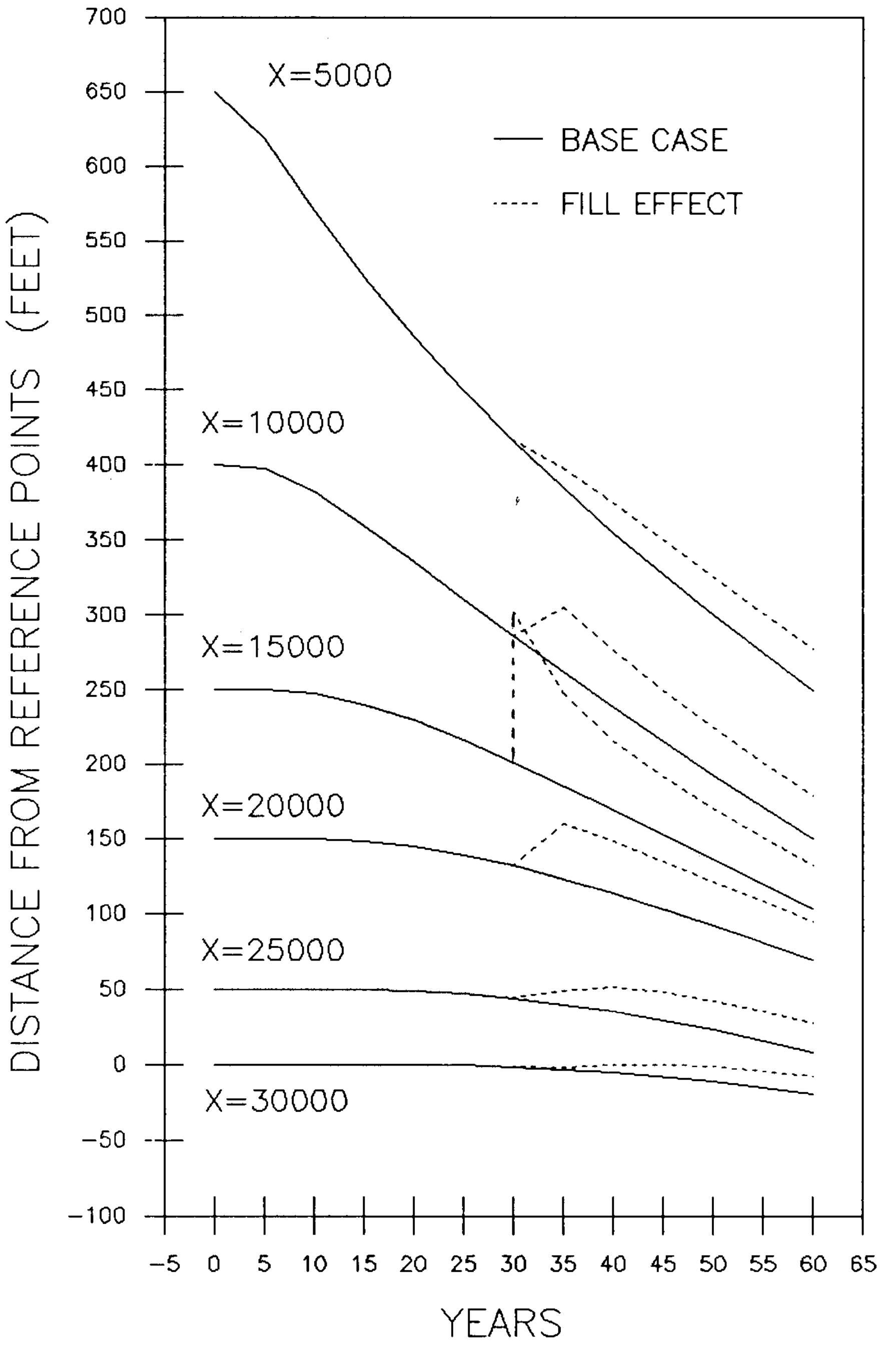


FIG. 4B — FILL AWAY FROM INLET CASE
DIST. VS. TIME PLOTS

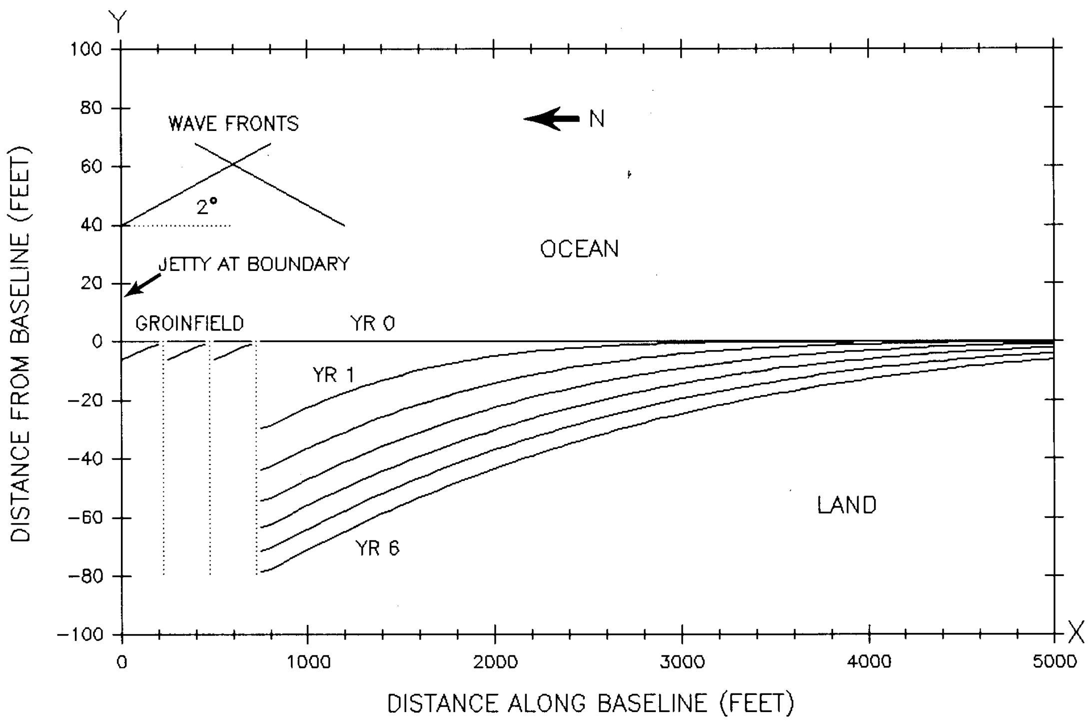


FIG. 5A — PLAN VIEW, GROINFIELD BASE CASE

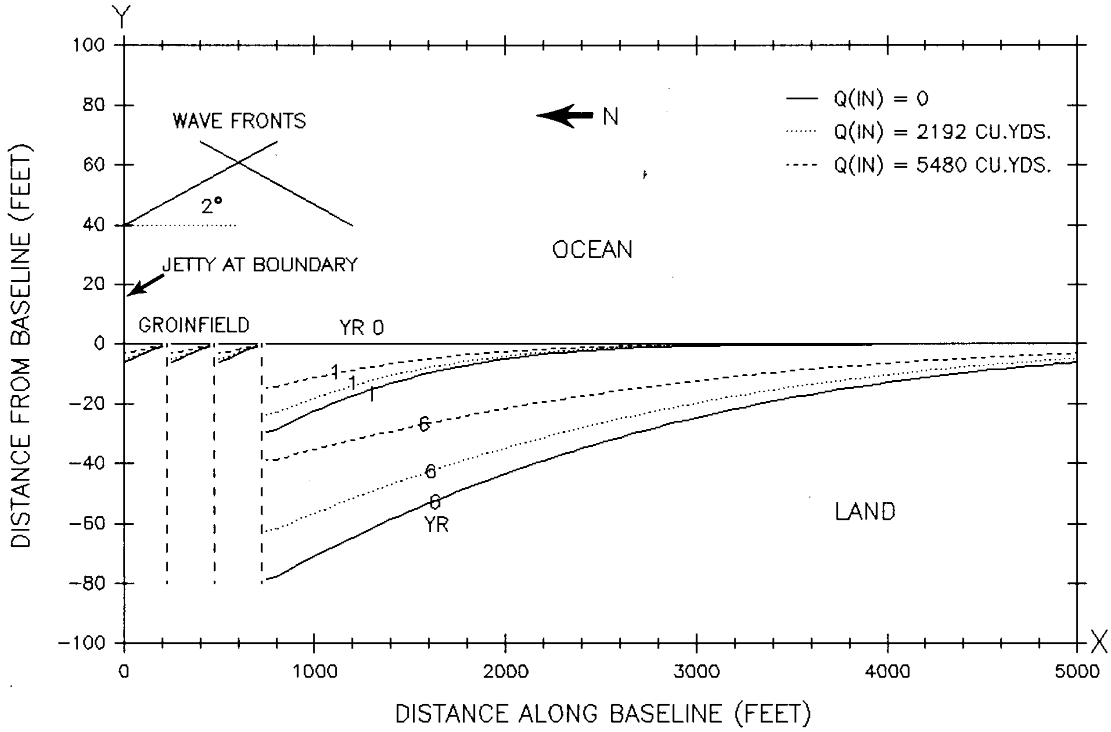


FIG. 5B – GROINFIELD CASE, EFFECT OF INCREASING Q(IN)

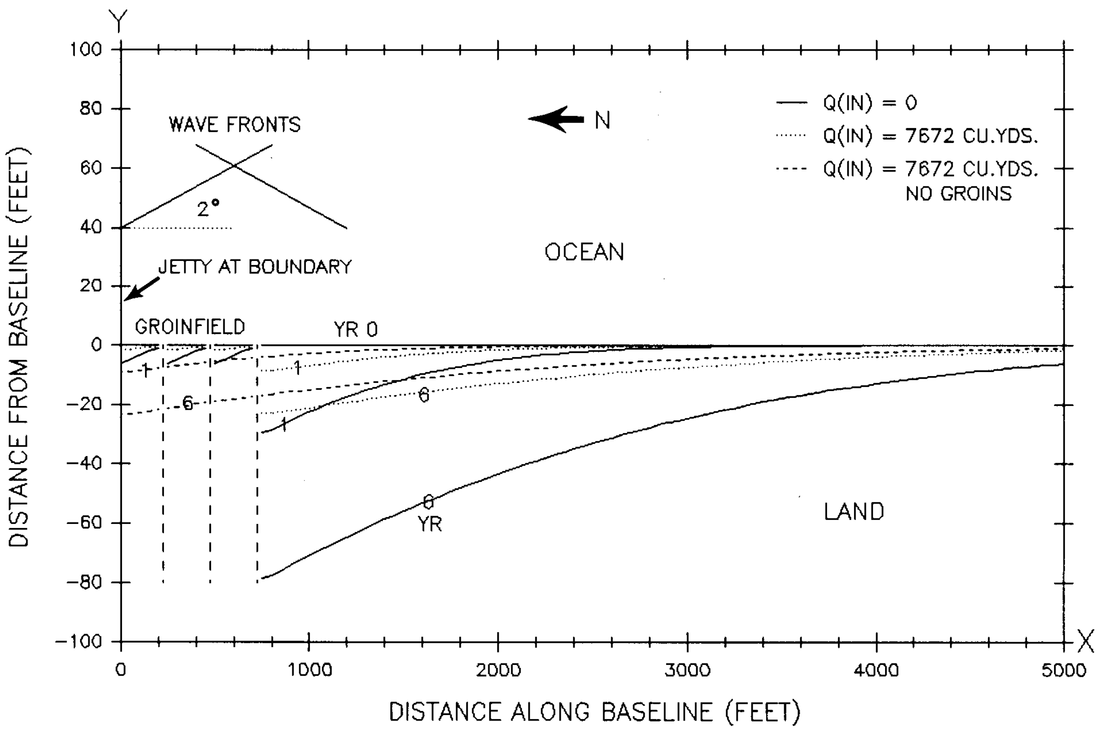


FIG. 5C – GROINFIELD CASE, GROINS VS. NO GROINS

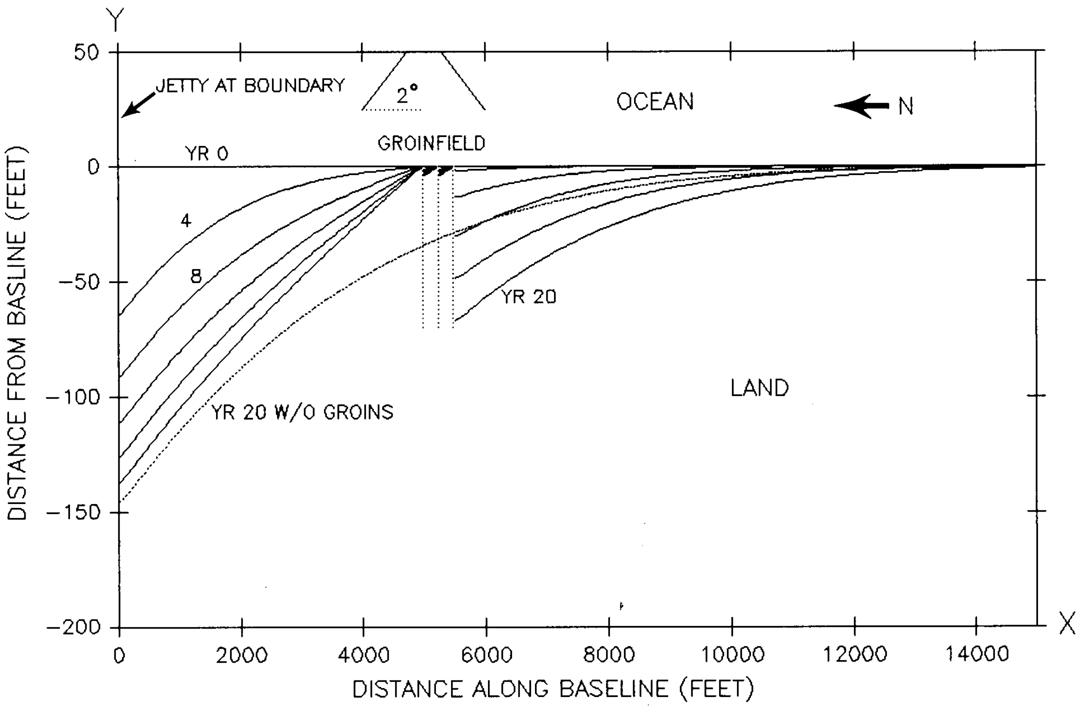


FIG. 6A — PLAN VIEW, GROINS AWAY FROM INLET CASE

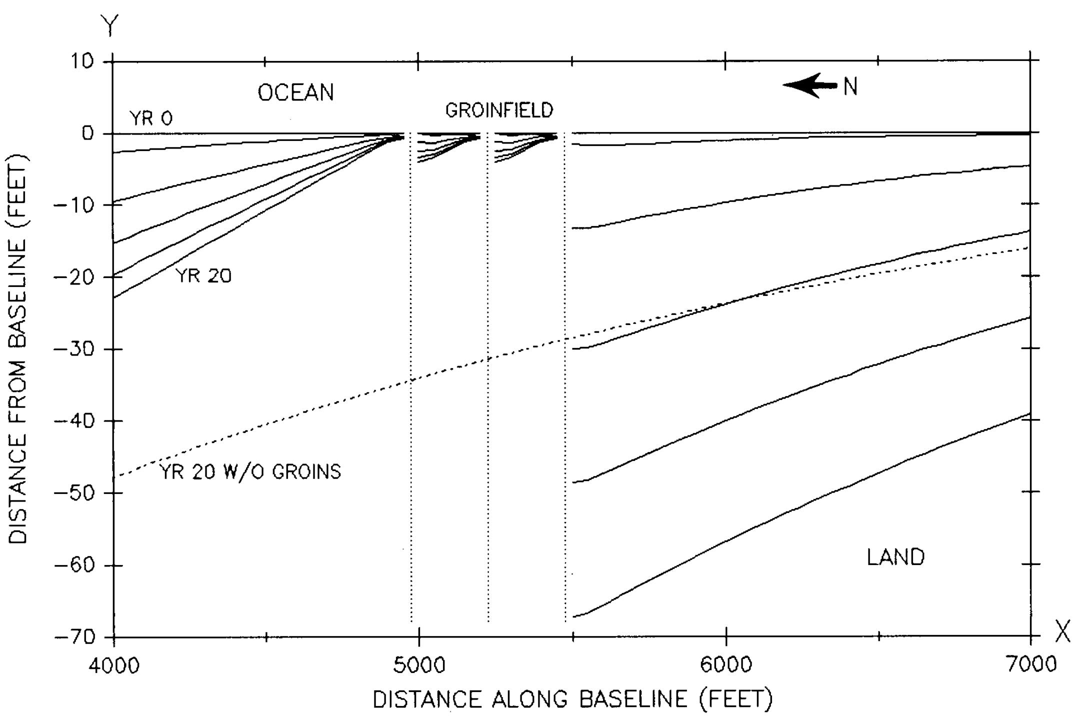


FIG. 6B — ENLARGEMENT, PLAN VIEW, GROINS AWAY FROM INLET CASE

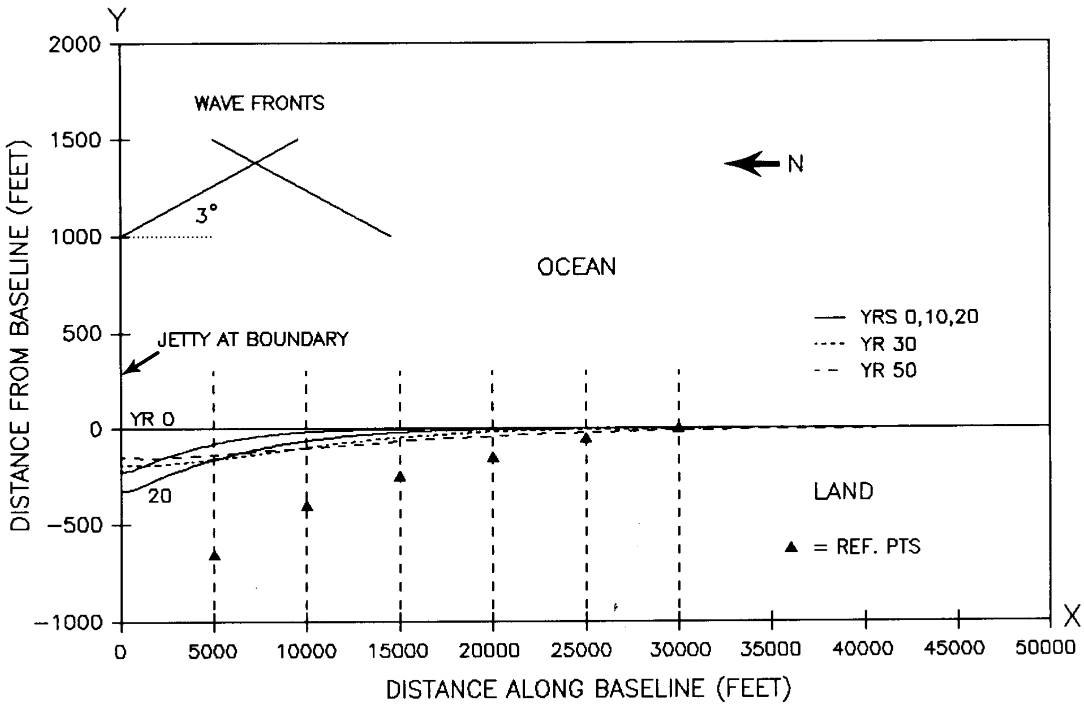


FIG. 7A – PLAN VIEW, POINT SOURCE CASE

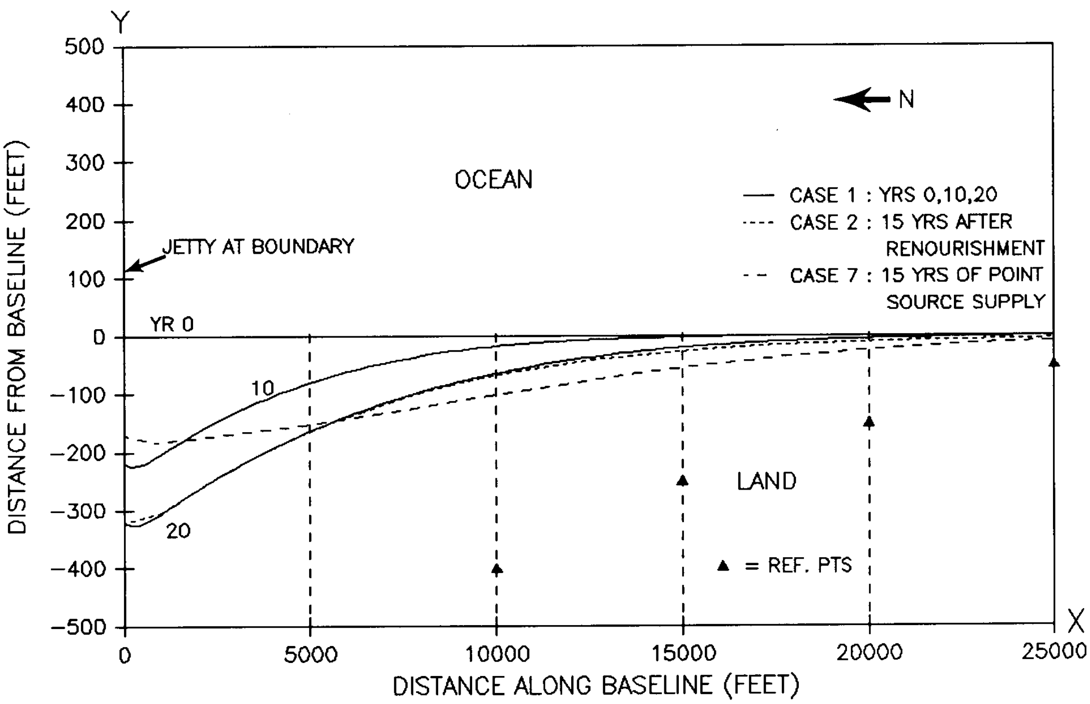


FIG. 7B – ENLARGEMENT, PLAN VIEW, POINT SOURCE VS RENOURISHMENT

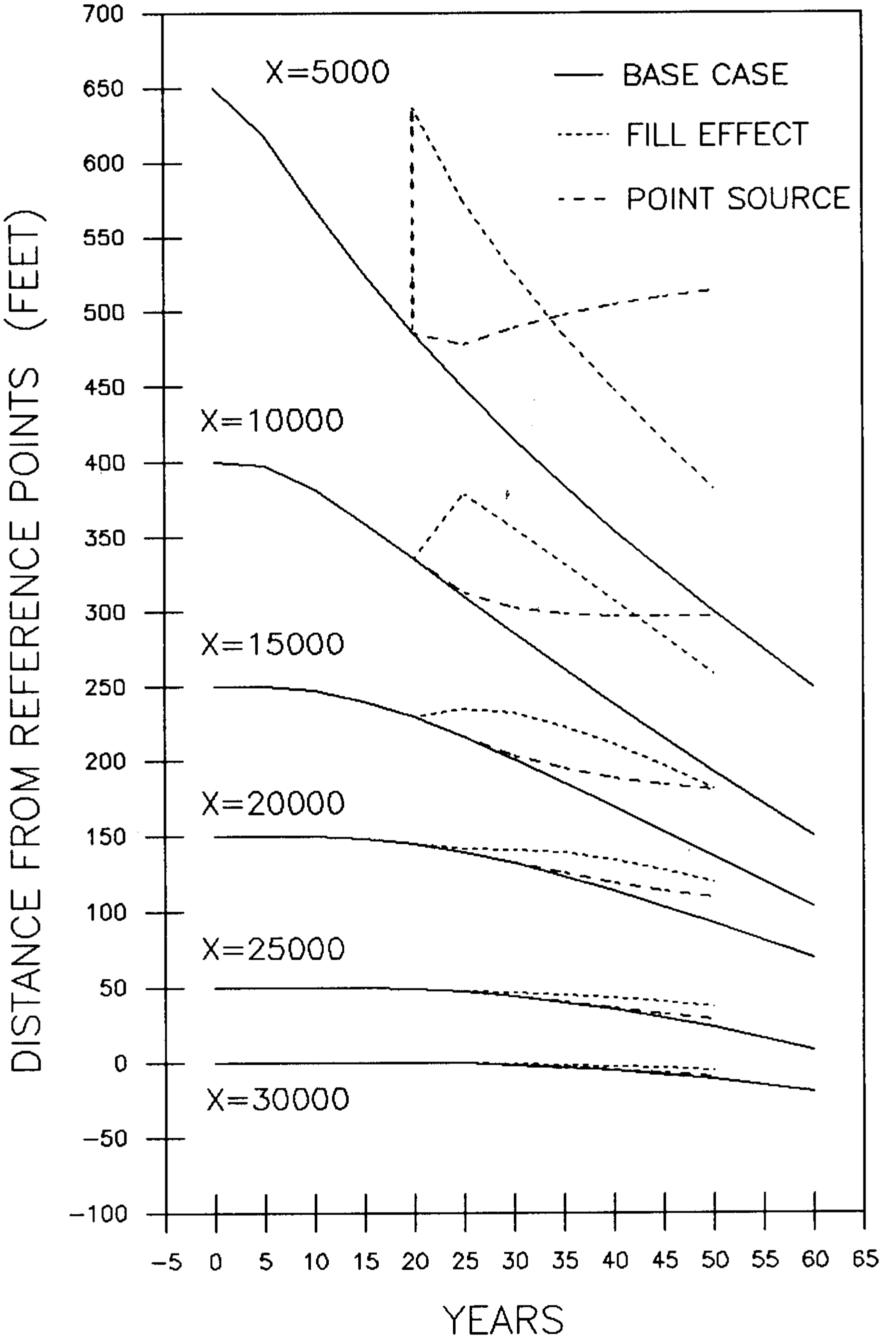


FIG. 7C - POINT SOURCE VS RENOURISHMENT,

DISTANCE VS TIME PLOTS

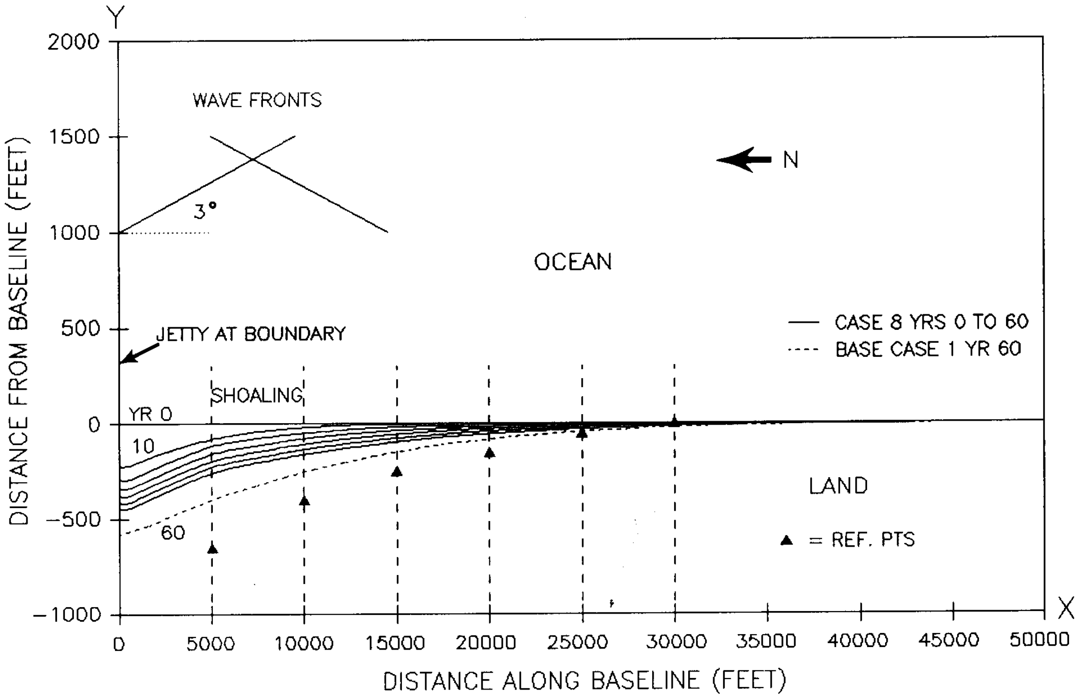


FIG. 8A – PLAN VIEW, SHOALING CASE

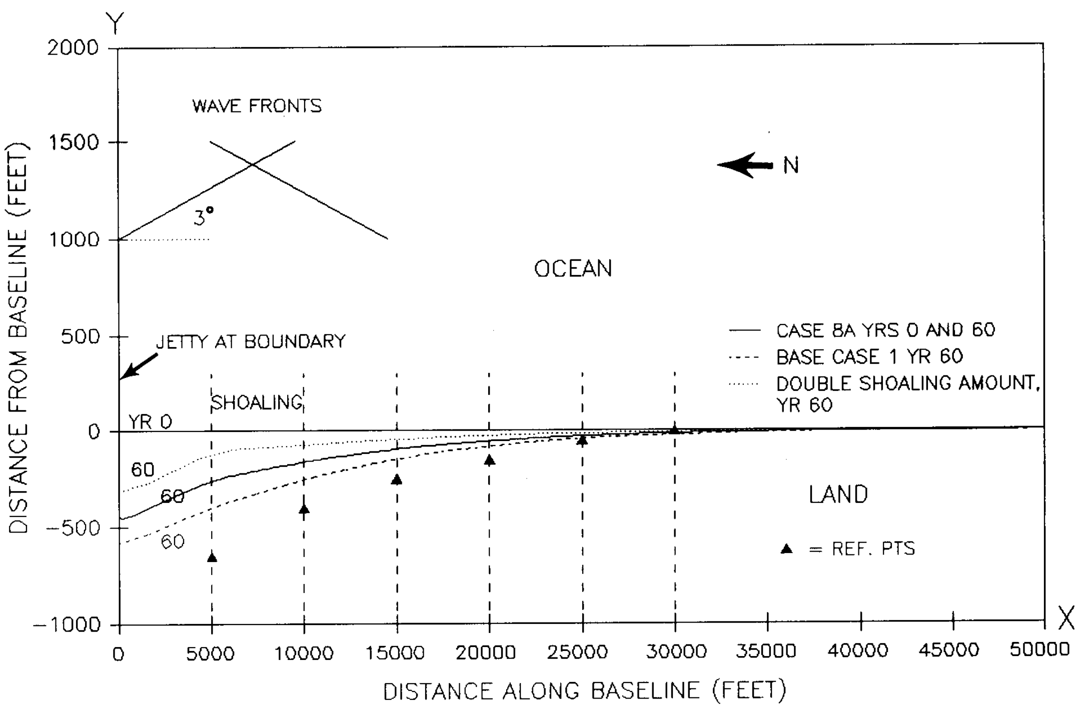


FIG. 8B – PLAN VIEW, SHOALING CASES VS. BASE CASE

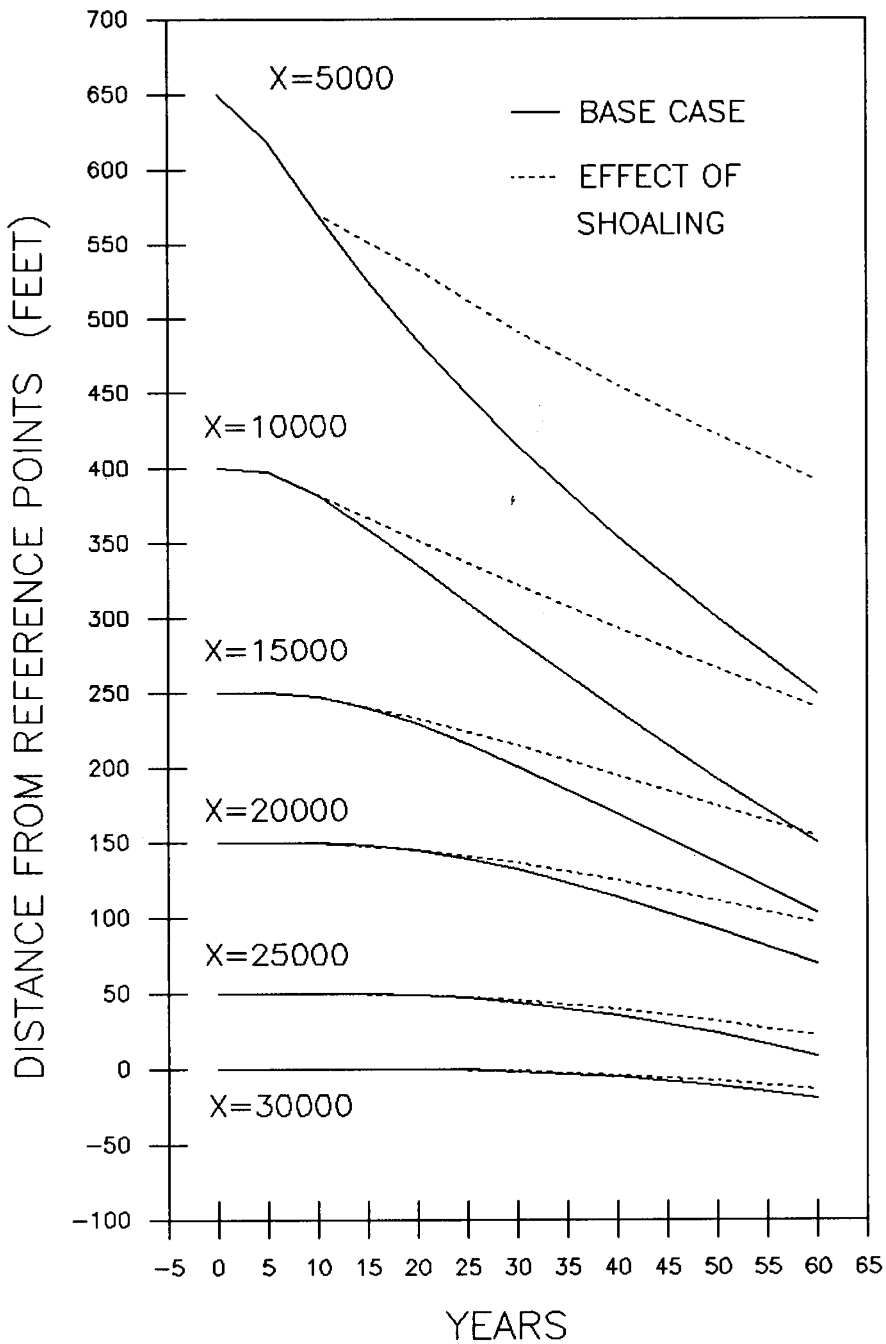


FIG. 8C – SHOAL CASE, DIST. VS. TIME PLOTS

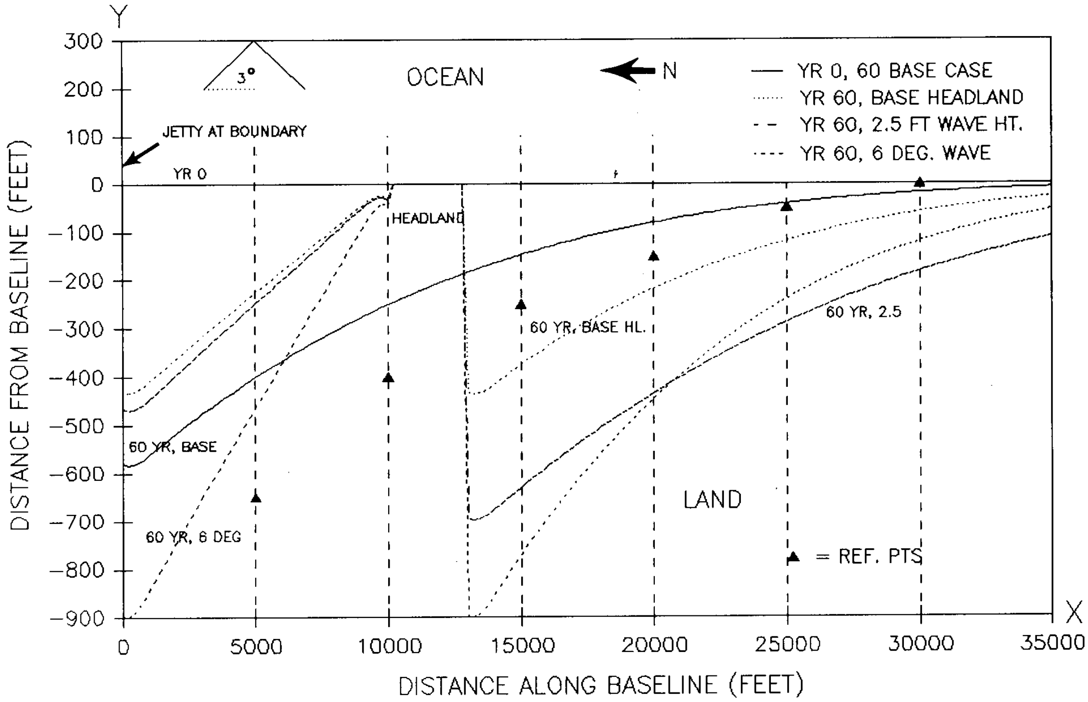


FIG. **9A** – NEARBY HEADLAND EFFECT

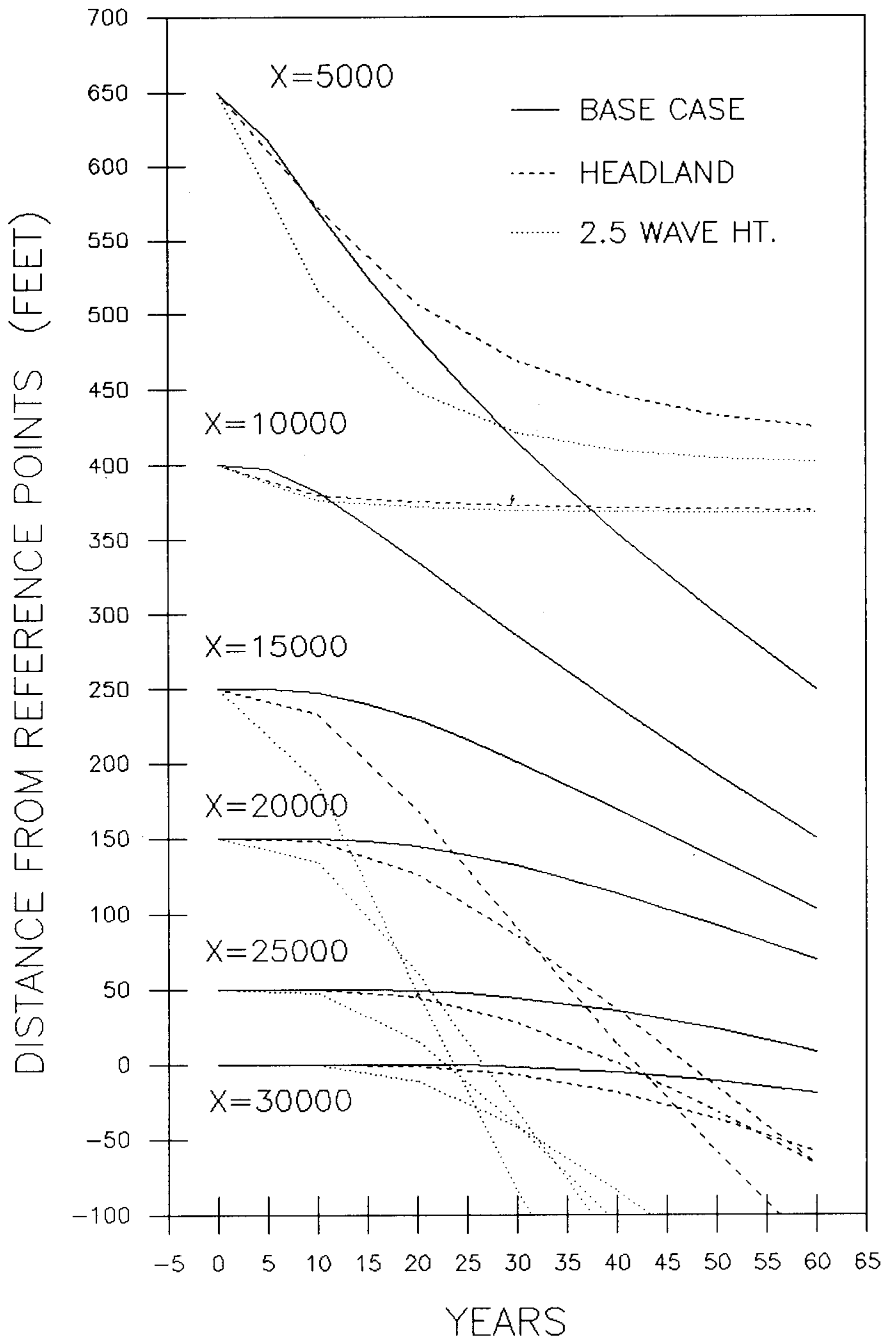


FIG. **9B** – NEARBY HEADLAND, WAVE HT. EFFECT
DIST. VS. TIME PLOTS

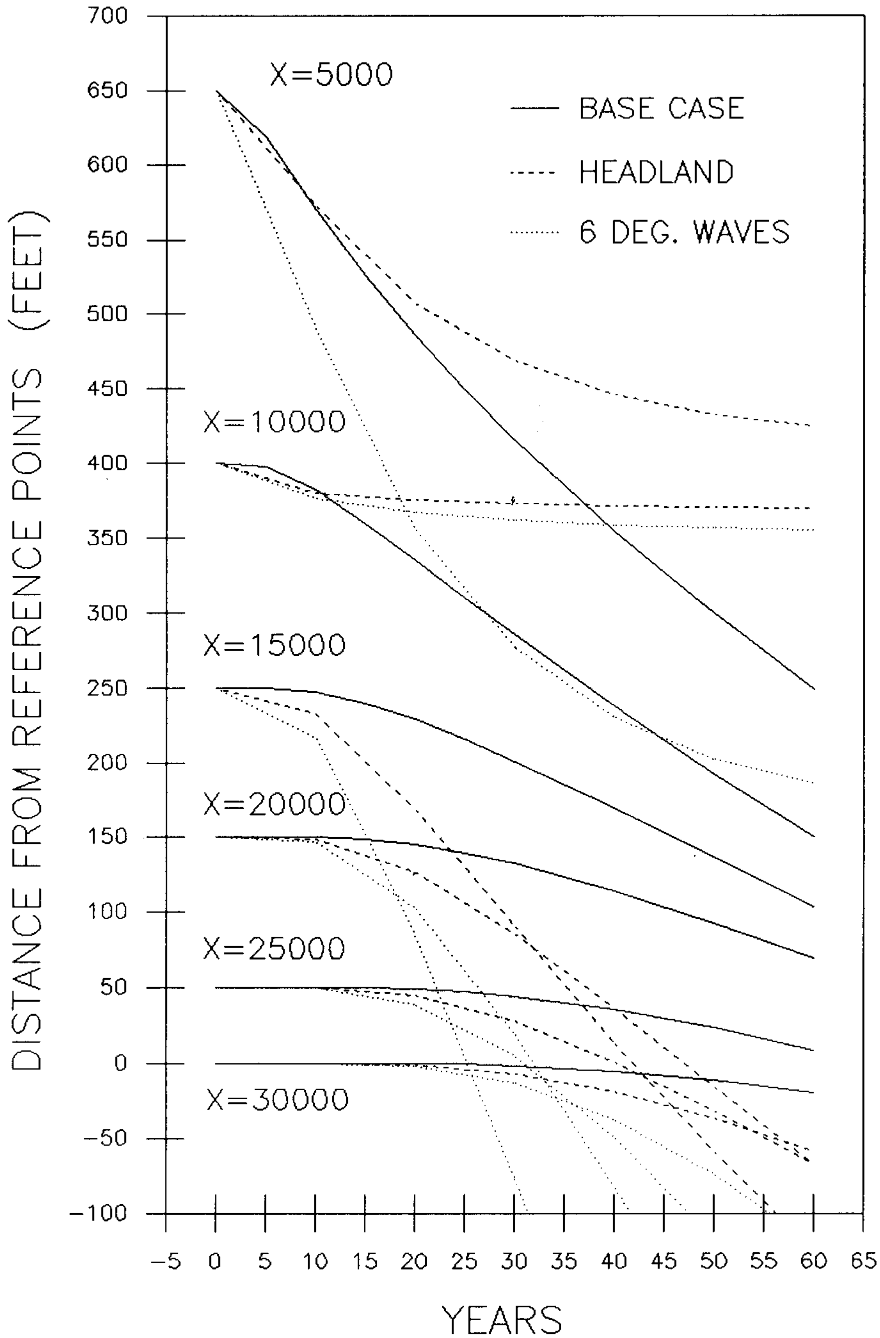


FIG. **9C** – NEARBY HEADLAND, WAVE ANGLE EFFECT DIST. VS. TIME PLOTS

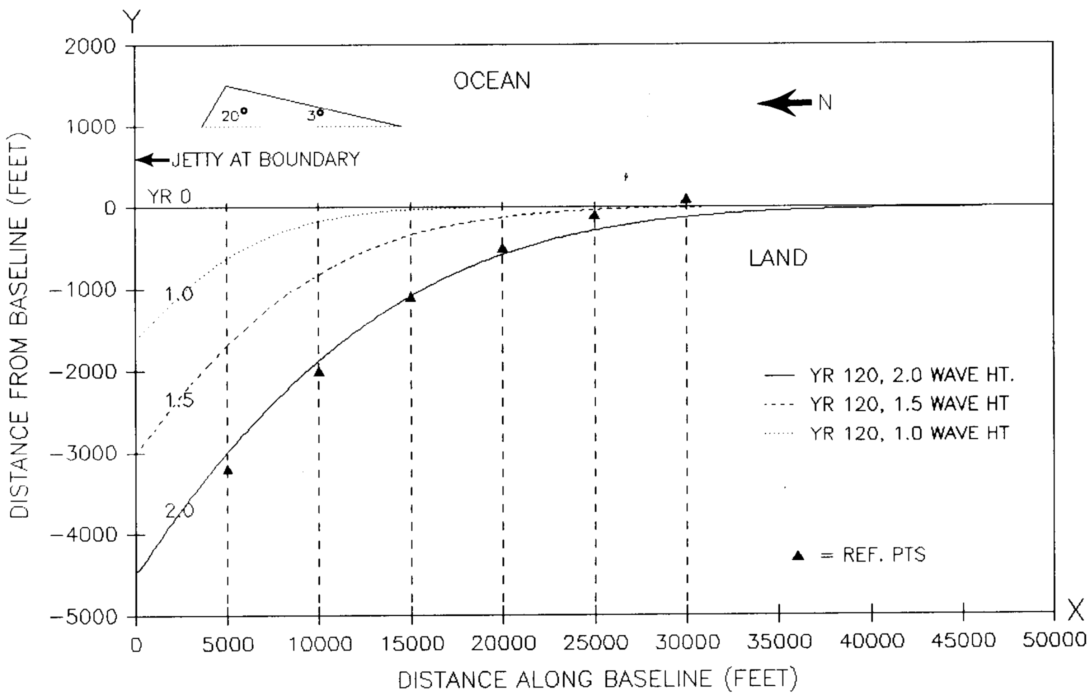


FIG. 10A - WAVE HEIGHT EFFECT OVER 120 YEARS

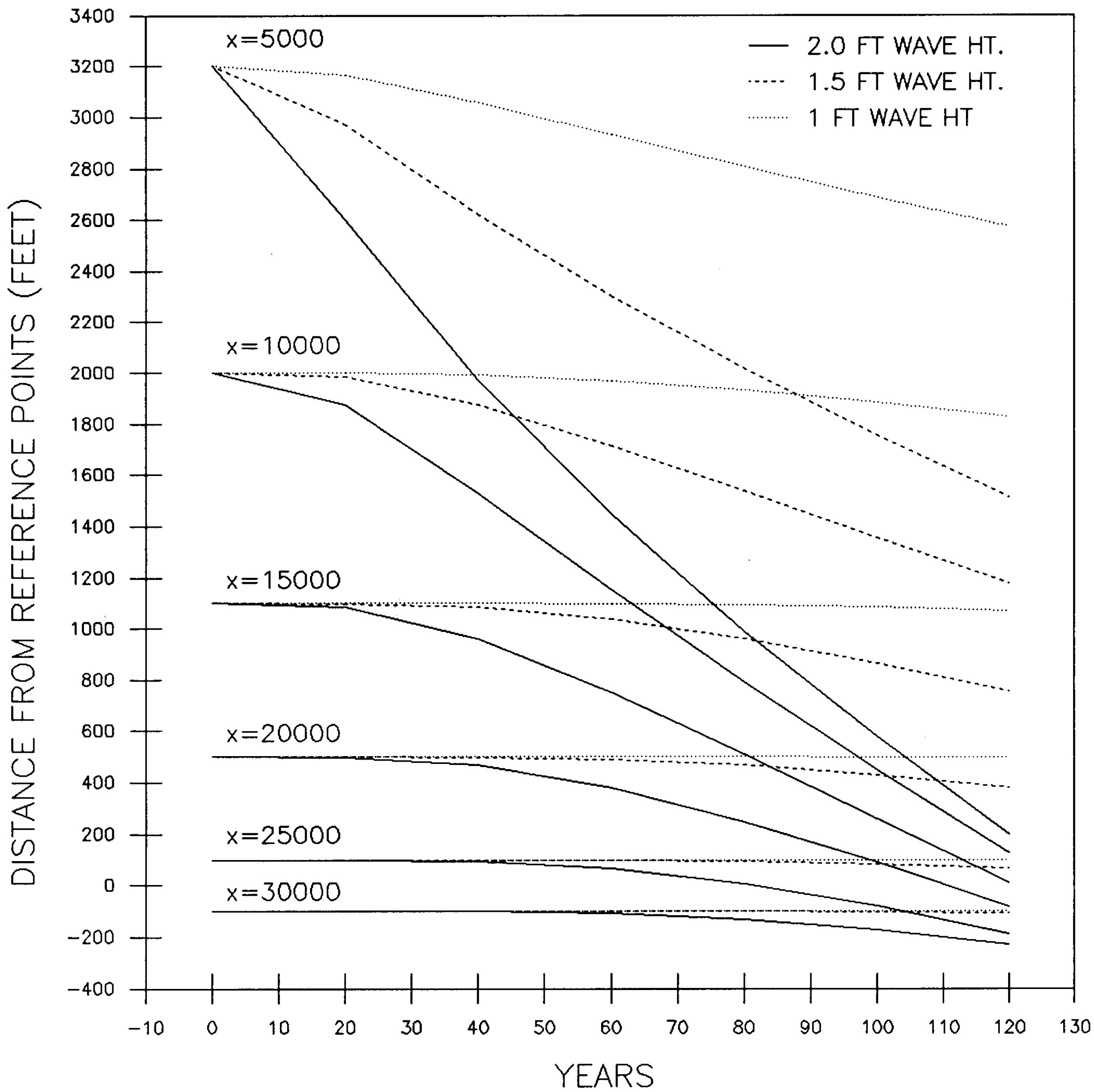


FIG. 10B — WAVE HEIGHT EFFECT, DIST. VS. TIME PLOTS

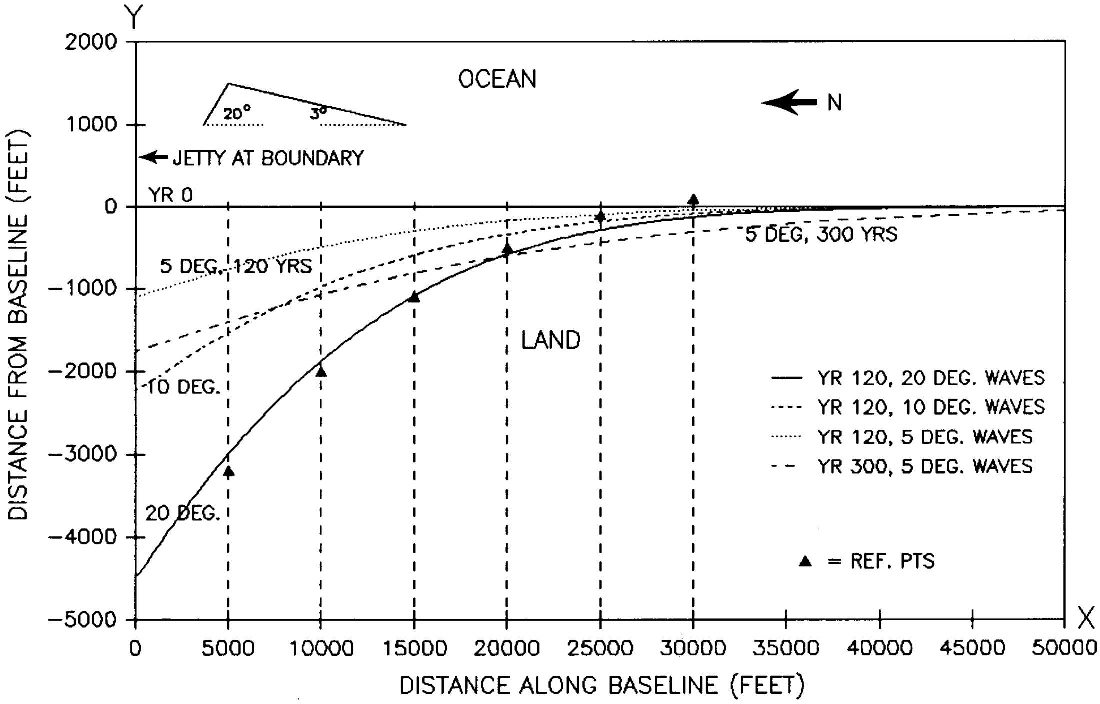


FIG. 10C – WAVE ANGLE EFFECT OVER 120 AND 300 YEARS

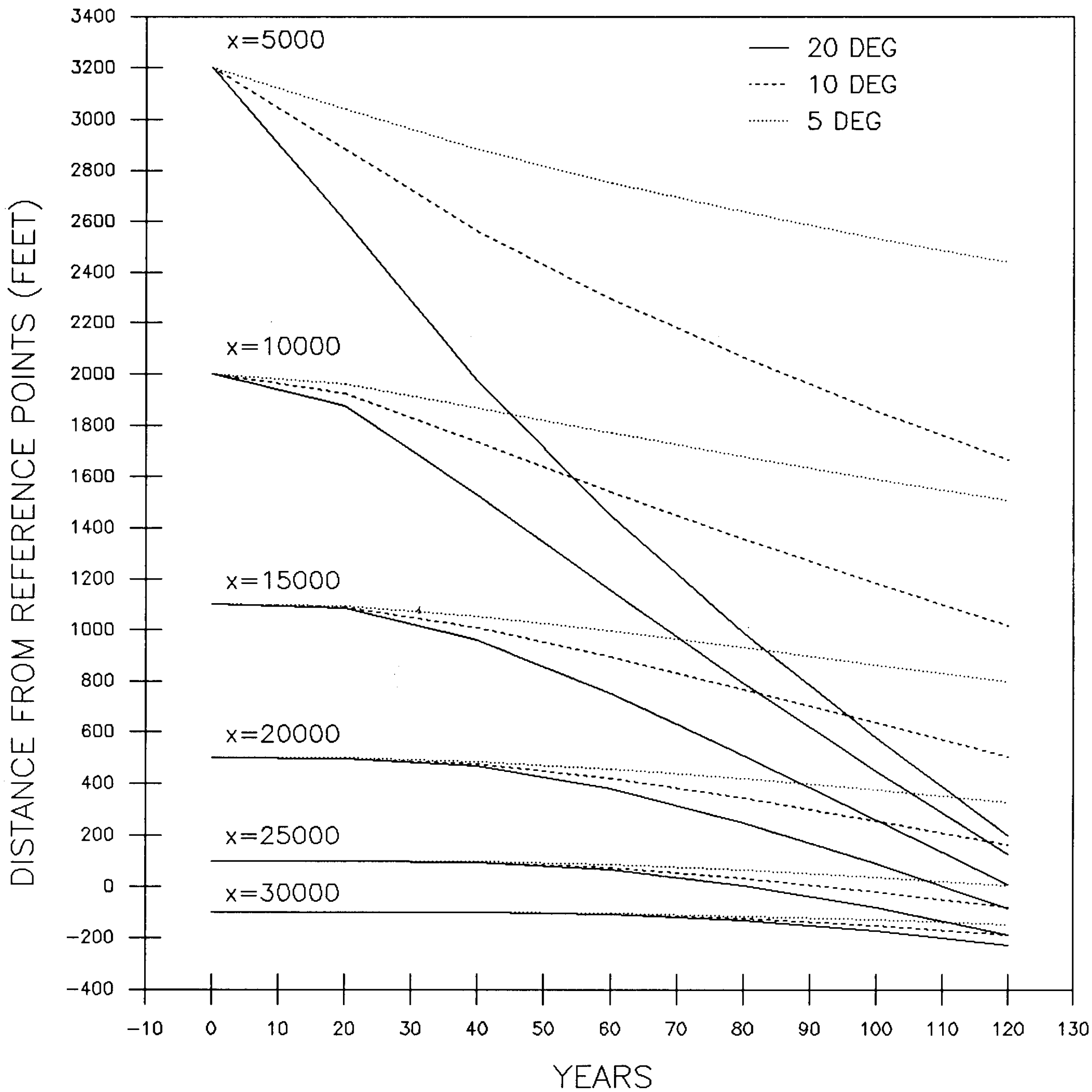


FIG. **10D** — WAVE ANGLE EFFECT, DIST. VS. TIME PLOTS

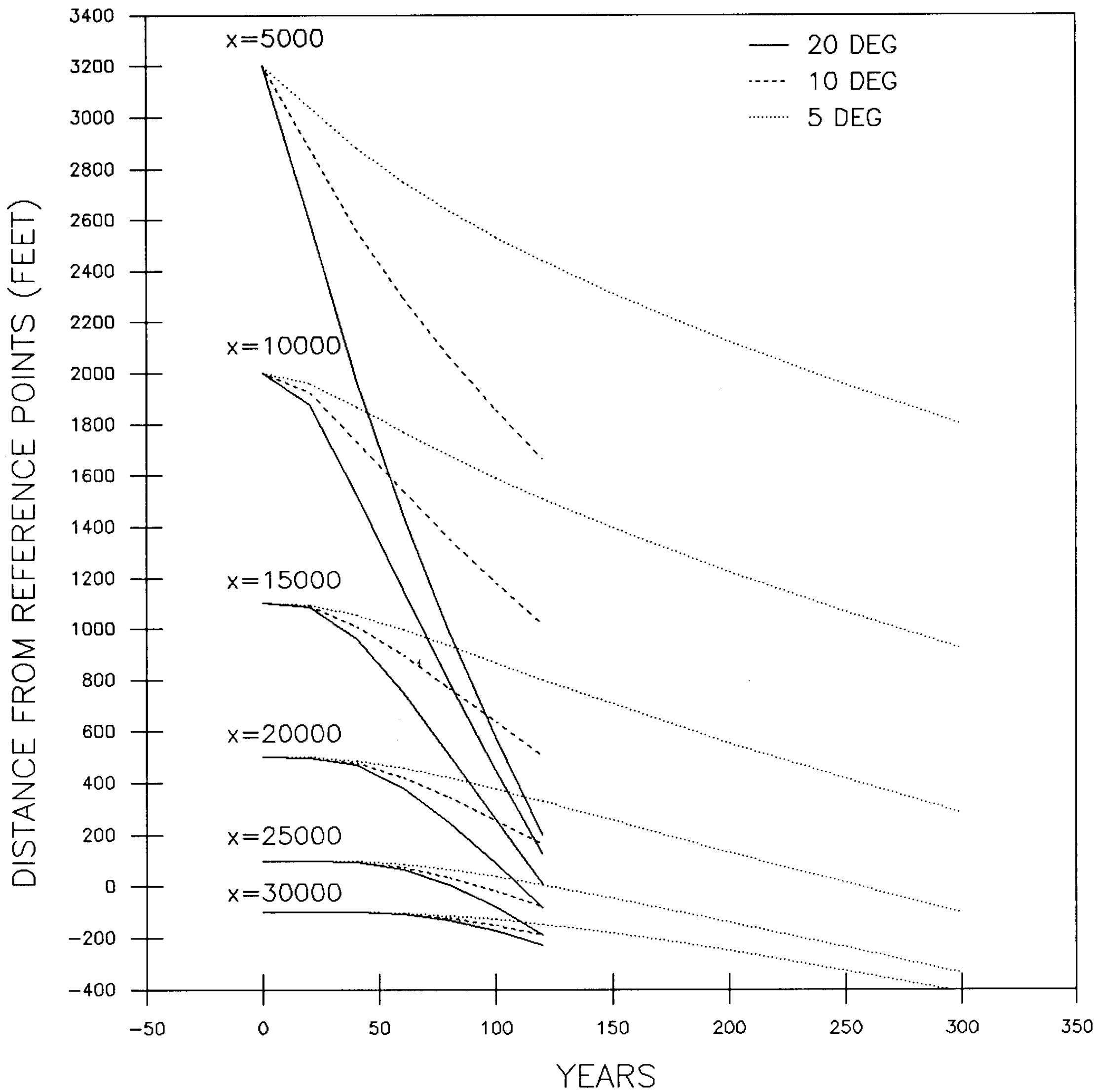


FIG. 10E — WAVE ANGLE EFFECT, 300 YEARS, DIST. VS. TIME PLOTS

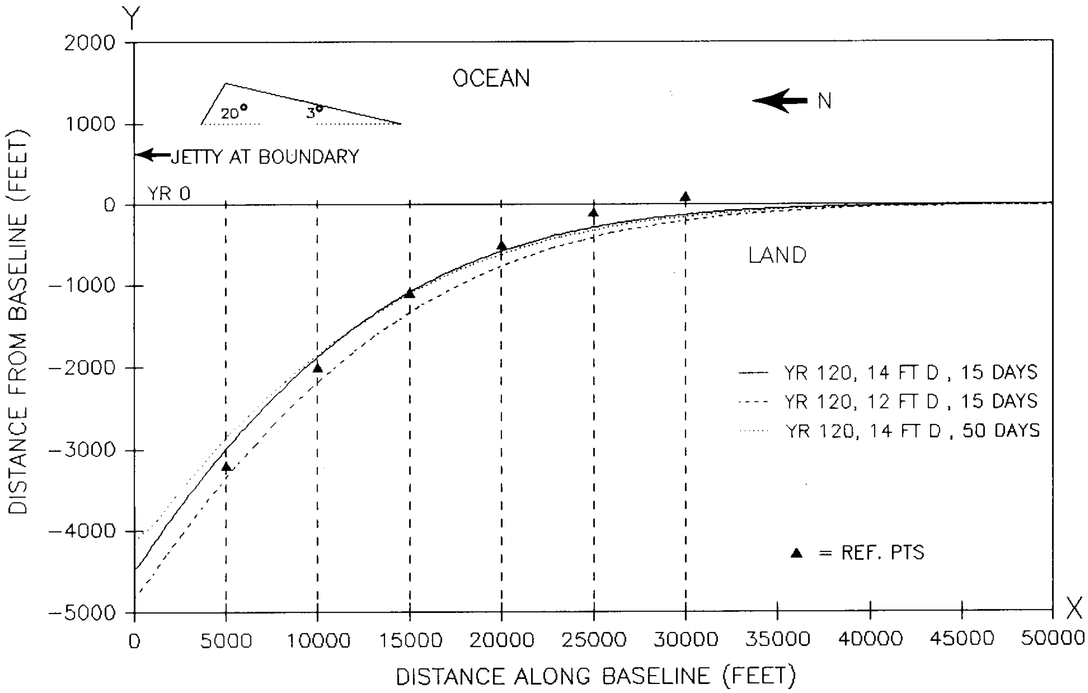


FIG. 10F – DEPTH AND SEASON 2 DURATION EFFECTS

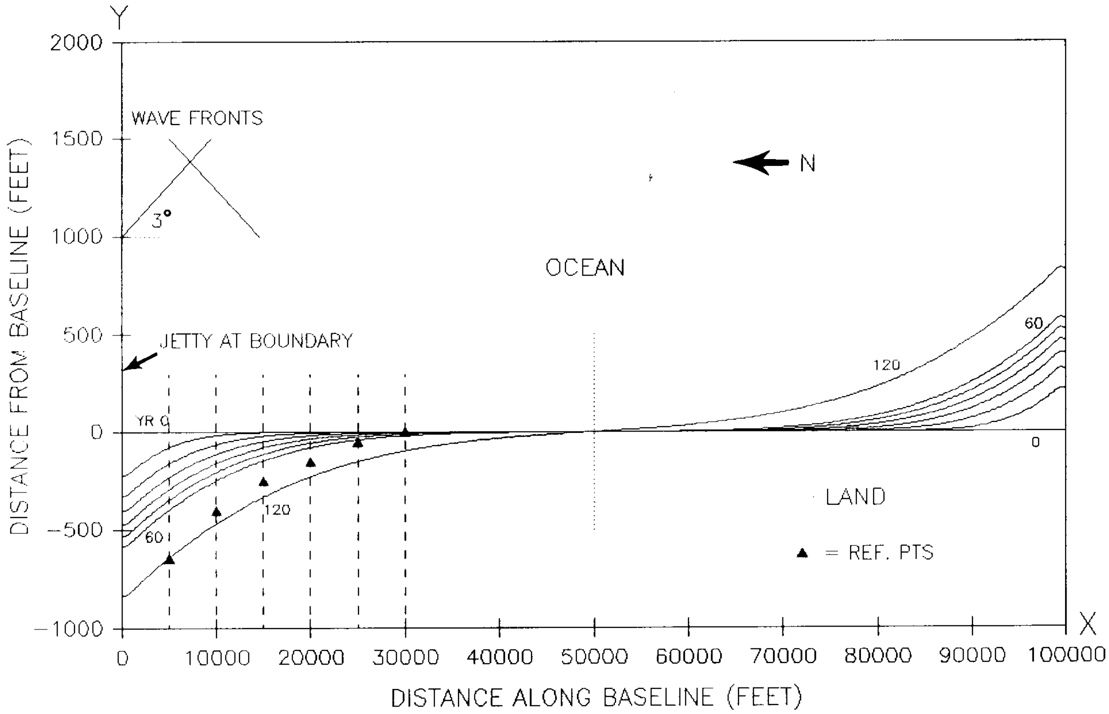


FIG. 11A – PLAN VIEW, BASE CASE, EQUAL END BOUNDARIES

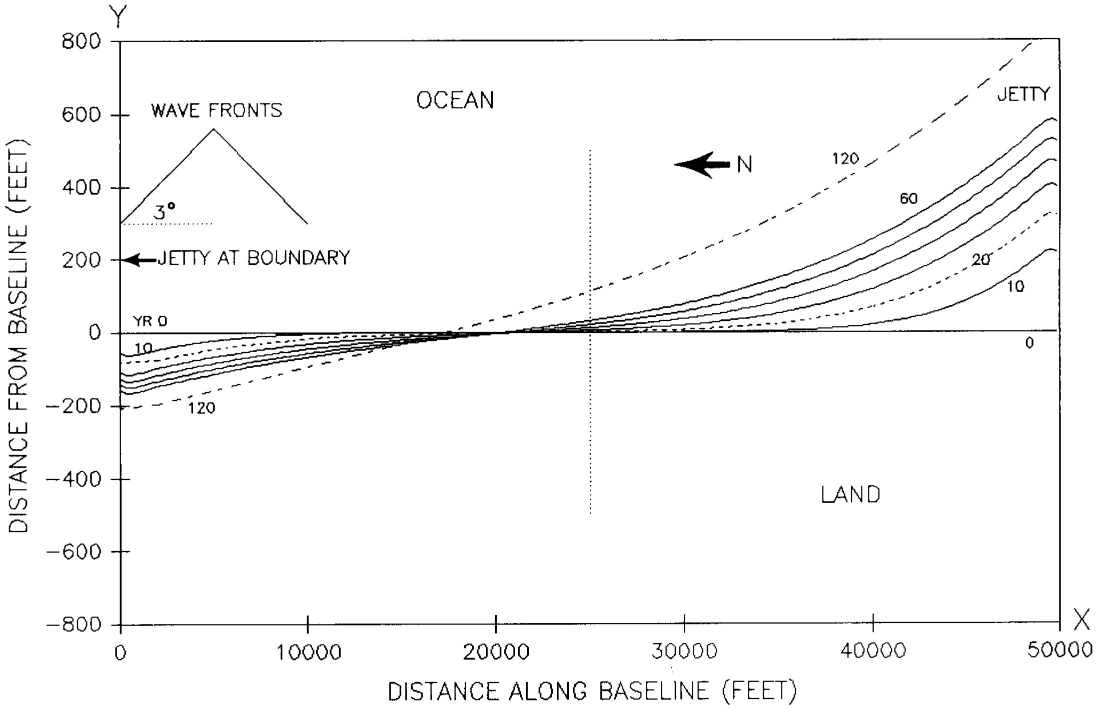


FIG. 11B – PLAN VIEW, POINT SOURCE AT NORTH BOUNDARY

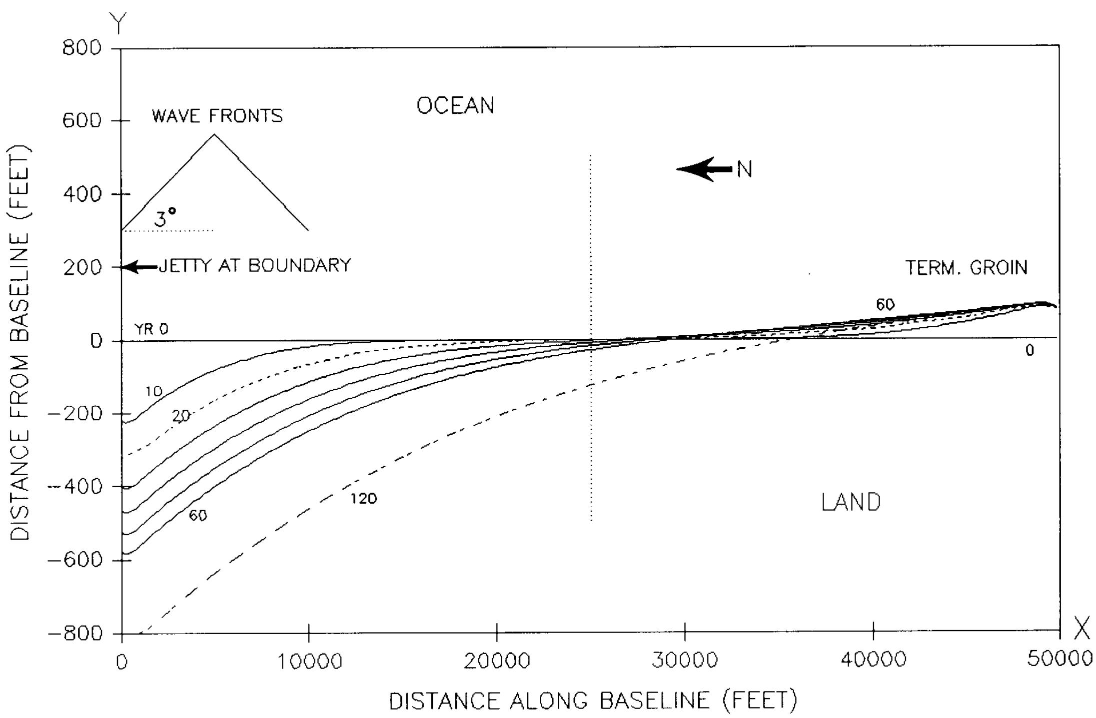


FIG. 11C – PLAN VIEW, TERMINAL GROIN SOUTH BOUNDARY

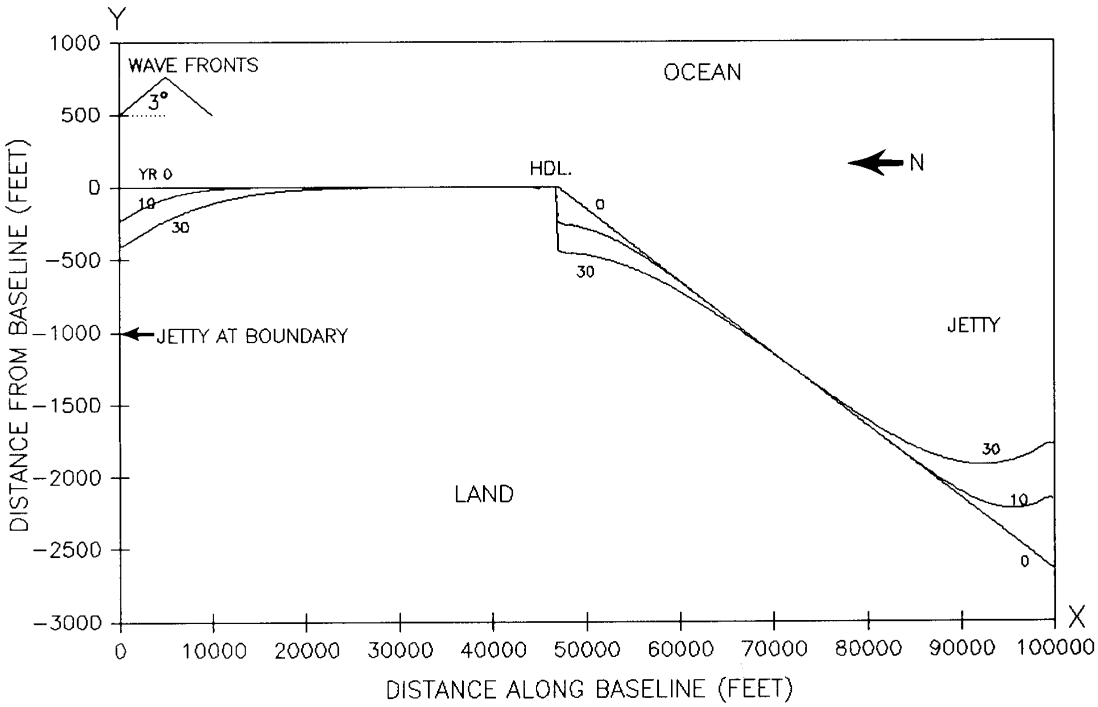


FIG. 11D – PLAN VIEW, HEADLAND & ORIENTATION EFFECT

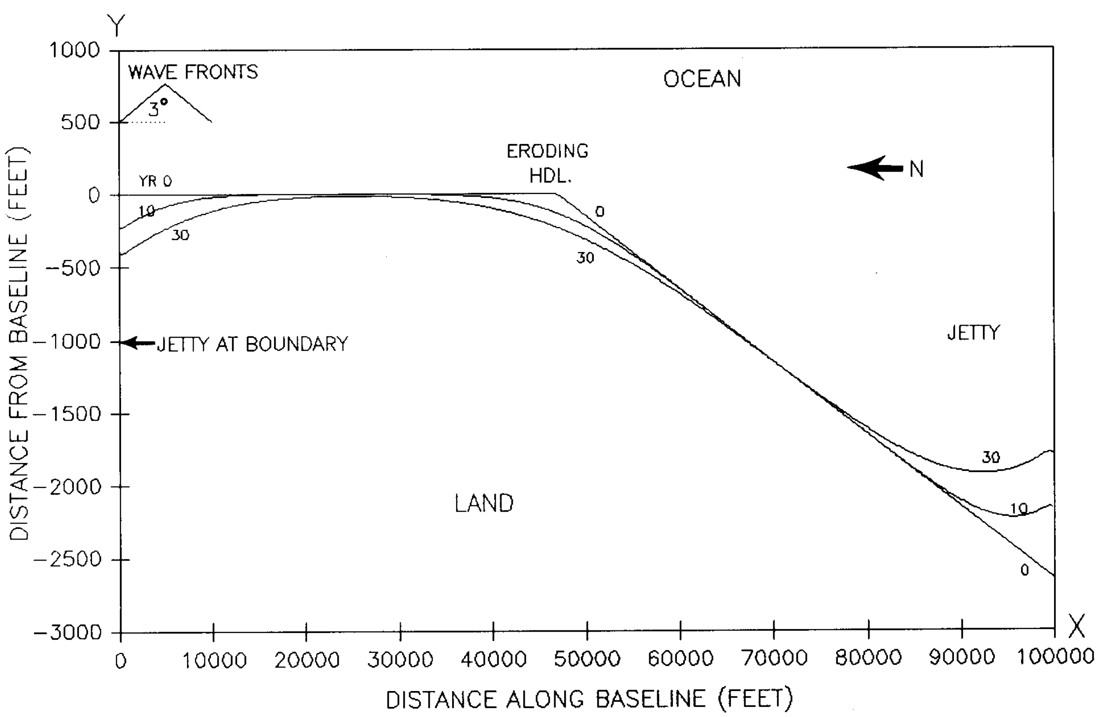


FIG. 11E – PLAN VIEW, ERODING HEADLAND & ORIENTATION EFFECT

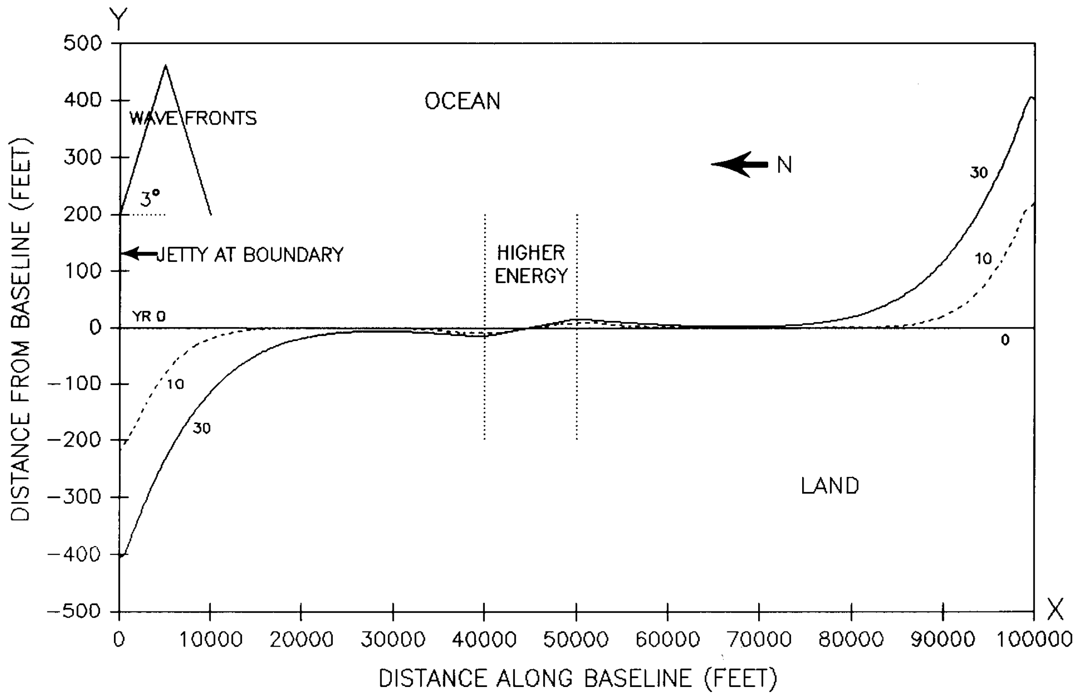


FIG. 11F — PLAN VIEW, HIGHER WAVE ENERGY ZONE

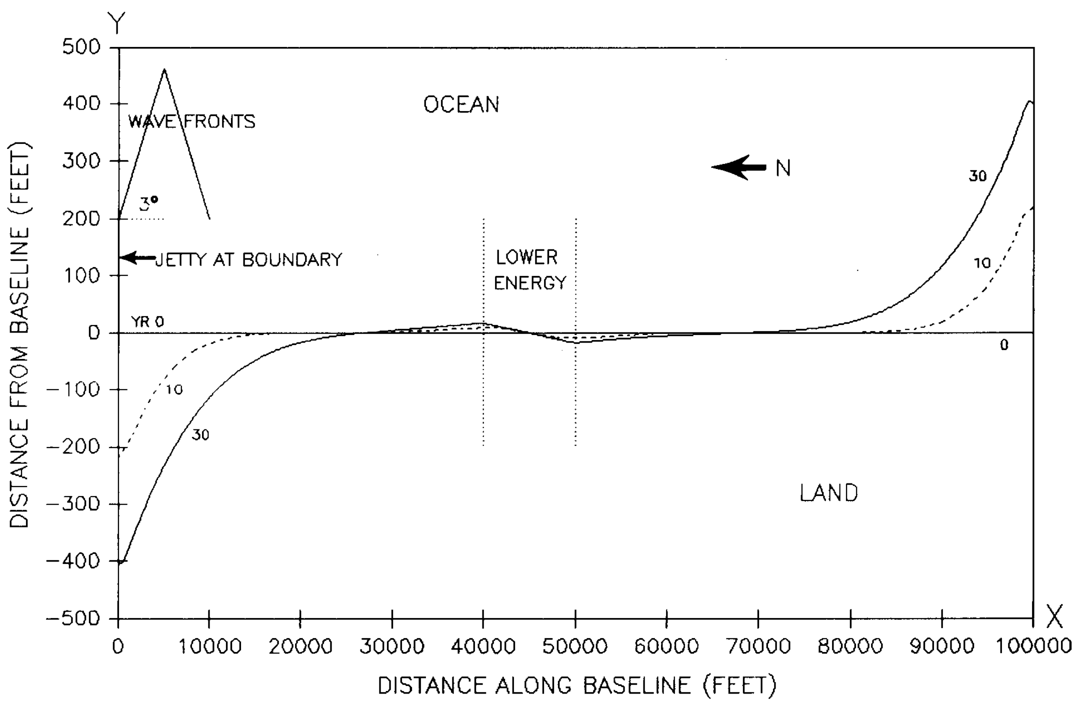


FIG. 11G — PLAN VIEW, LOWER WAVE ENERGY ZONE

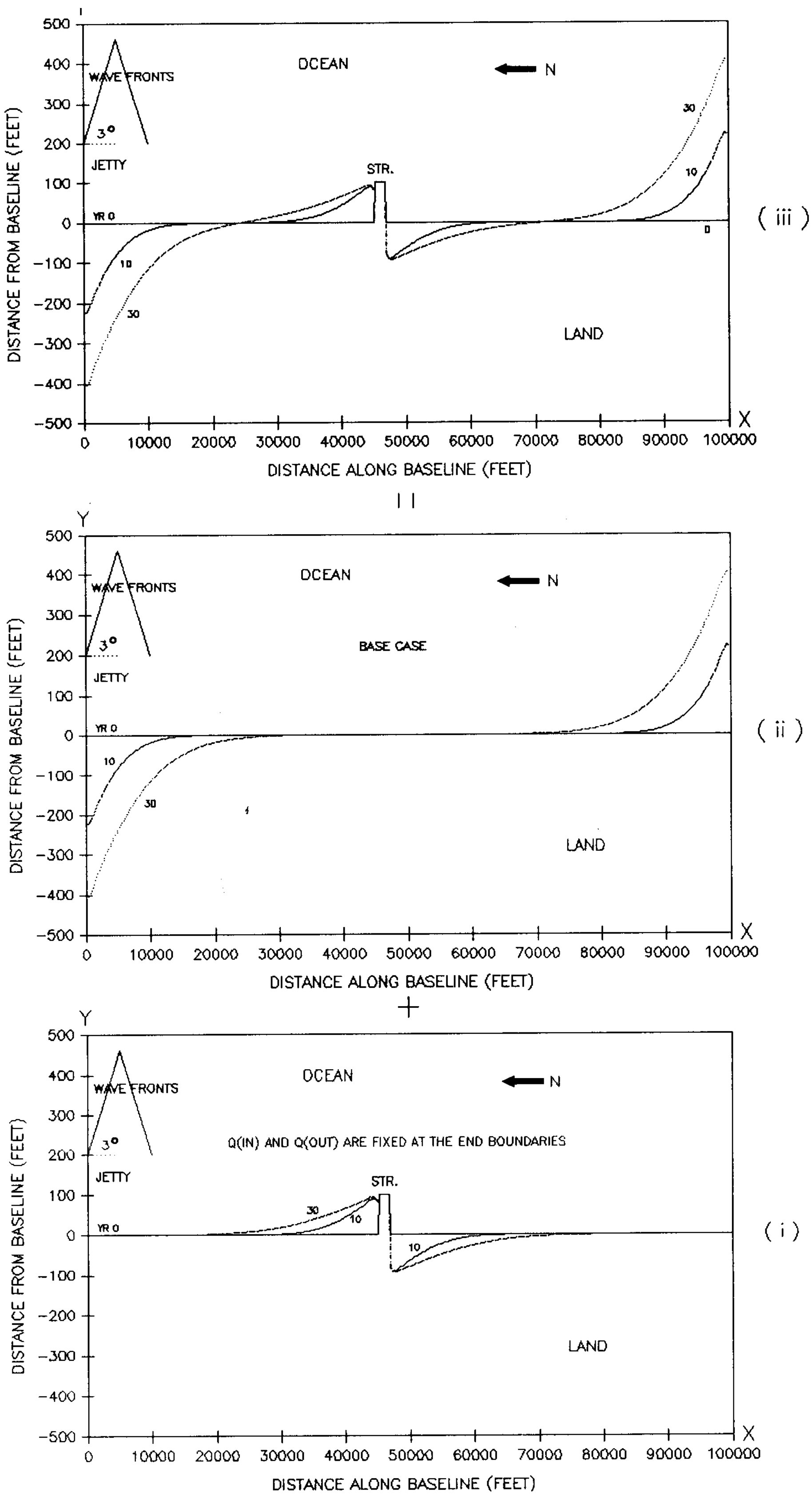


FIG. 12A - SUPERIMPOSING EFFECTS, STRUCTURE EXAMPLE

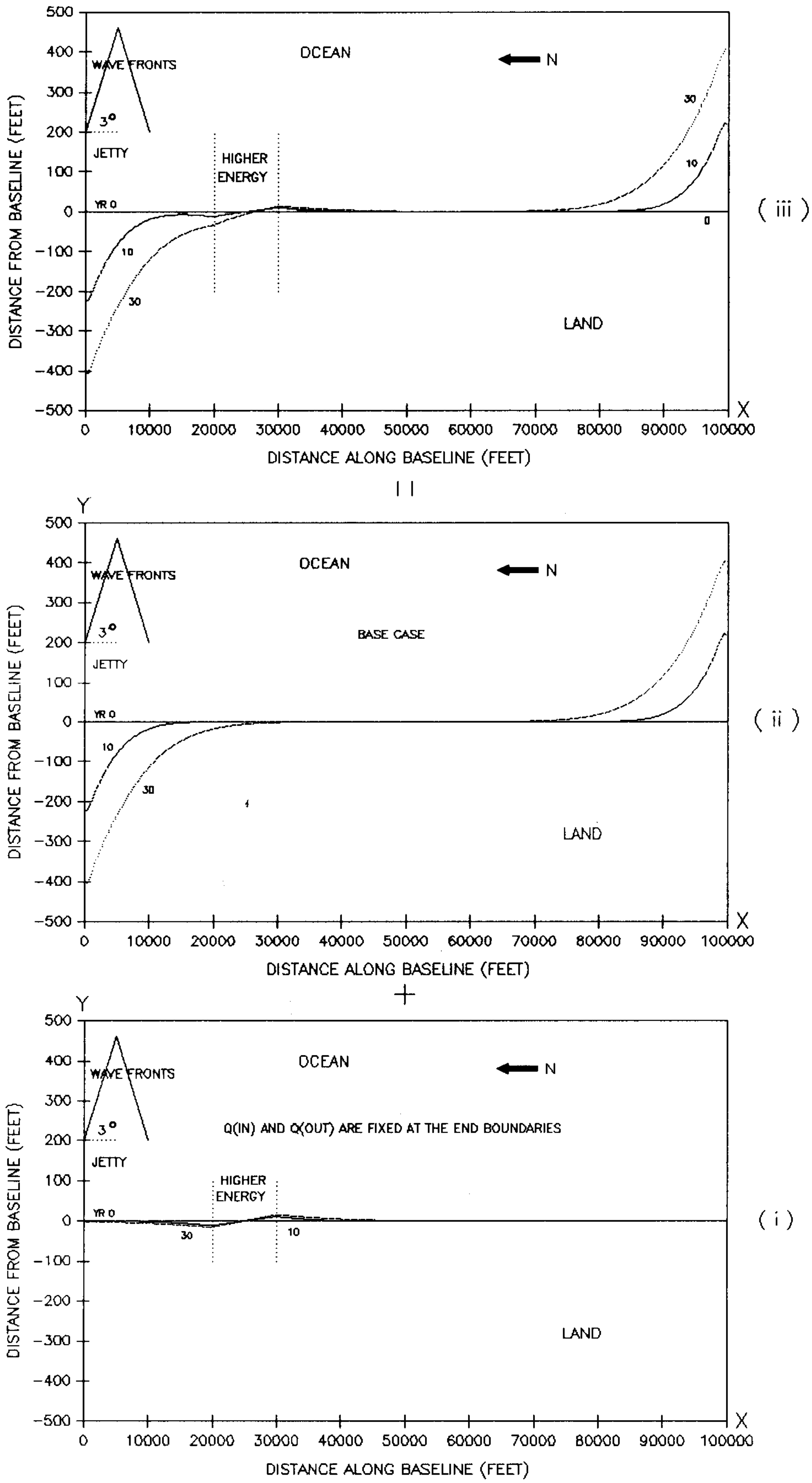


FIG. 12B - SUPERIMPOSING EFFECTS, ENERGY EXAMPLE

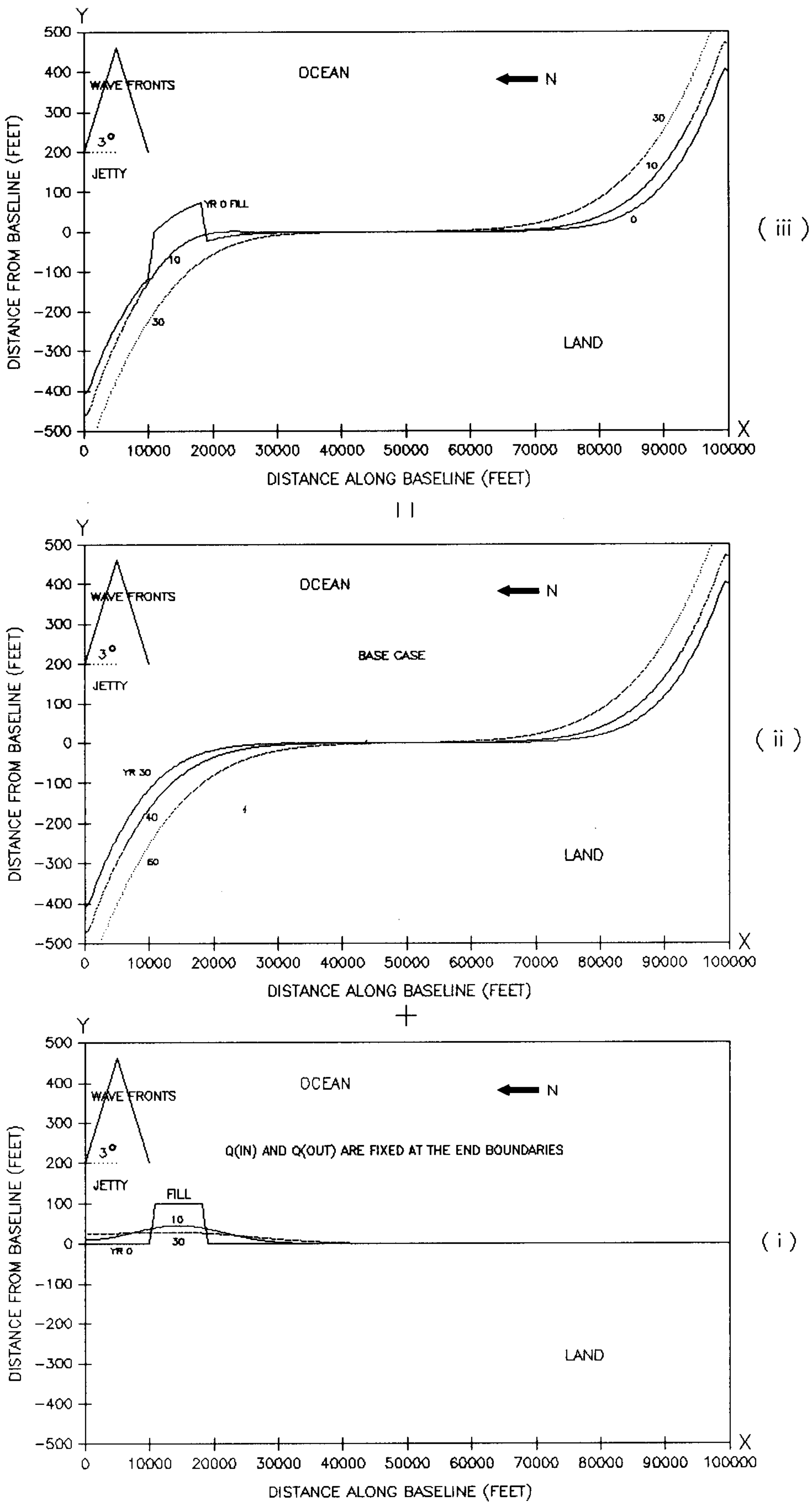
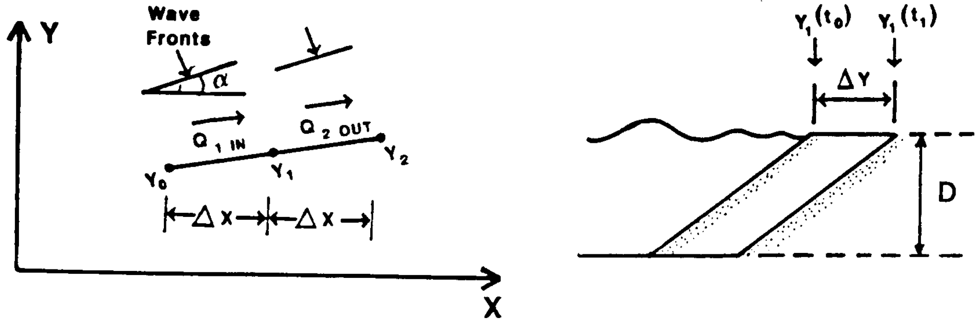


FIG. 12C - SUPERIMPOSING EFFECTS, FILL EXAMPLE

APPENDIX

Two Season, One Line, Longshore Model
Definition Sketch and General Equations



For any time step Δt:
if $Q_{1in} > Q_{2out}$, then Y_1 shoreline position advances;
if $Q_{1in} < Q_{2out}$, then Y_1 shoreline position recedes.

$$Q_{1in} = K \bullet \sin(2 \bullet (\alpha - \tan^{-1}(Y_1 - Y_0/\Delta X)))$$

$$Q_{2out} = K \bullet \sin(2 \bullet (\alpha - \tan^{-1}(Y_2 - Y_1/\Delta X)))$$

$$K = (k \bullet (g/k_d)^{0.5} \bullet H_b^{2.5})/(16 \bullet (s-1) \bullet (1-p))$$

$$Y_1(t_1) = Y_1(t_0) - ((\Delta t/(D \bullet \Delta X)) \bullet (Q_{2out} - Q_{1in}))$$

where:

Q = sediment transport in cu.ft./sec.
Y_i = shoreline location at x interval "i", in feet
g = 32.2 ft./sec^2 = gravity
k_d = 0.78 = ratio of breaking wave height to water depth
k = 0.77 = proportionality factor, recommended value
D = total depth of parallelogram cross-section, in feet
H_b = breaking wave height in feet
s = specific gravity of the sediment = 2.65
p = inplace porosity of the sediment = 0.35
t = time in seconds
Δt = time step in seconds
ΔX = x interval in feet
α = angle of the breaking wave crest with the x axis

Two Wave Climate Seasons:

The model is run for a selected number of days with waves from one direction in order to simulate season #1 (e.g. average winter conditions). The model is then run for another selected number of days with waves from another direction, to simulate season #2 (e.g. average summer conditions). The sequence of the two seasons represents one year of average wave activity. The model can be run for any number of years.

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