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OCEANICS INC.

A STUDY OF BERTHING ARRANGEMENTS FOR NUCLEAR SUBMARINES AT THE NEW LONDON SUBMARINE BASE

by

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Prepared for:

Eastern Division
Naval Facilities Engineering Command
90 Church Street
New York, N. Y.

under

Contract No. NBy 70553(A & E)

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ABSTRACT

The problem of developing an optimum waterfront design for berthing nuclear submarines at the New London Submarine Base is treated primarily as an operational problem involving the interaction of the submarine with the physical environment of the channel. Preliminary investigation revealed that, of all the contributing elements, the presence of tidal currents is the single greatest deterrent to achievement of a successful landing. With due consideration of physical environment, servicing and operational logistics, and practicality of implementation, it is deemed feasible to develop a berthing arrangement that will satisfy all of these constraints. To evaluate the effectiveness of the proposed solution, a computer simulation experiment, of submarine landing, is developed and a parametric study is undertaken. Results show the optimum pier orientation and slip width appropriate to the present waterfront design. Additional experiments show that, for nuclear submarines, a sawtooth berthing arrangement is superior to the optimum conventional layout.

LIST OF NOTATION

$E_{-\frac{1}{3}}$	corresponds to submarine engine order of "back one-third"
$E_{T_{-\frac{1}{3}}}$	corresponds to tugboat engine order of "back one-third"
K_{Dm}	added mass correction factor
m	mass of submarine
$N(u,\delta)$	yaw moment due to rudder
r	angular speed about vertical axis of submarine
t	time
u	speed of submarine in direction of longitudinal axis
v	component speed of submarine in lateral direction
x_i and y_i	various coefficients of quasi-steady hydrodynamic forces
$Y(u,\delta)$	lateral force due to rudder
δ	rudder angle
ψ	yaw angle

INTRODUCTION

The Naval Facilities Engineering Command is engaged in a program of refurbishing the submarine berthing facilities on the Thames River at the New London Submarine Base. The purpose of renovation is to replace aging piers and in so doing to provide accommodation for a projected number of nuclear and conventional submarines as well as auxiliary miscellaneous vessels. The basic formula for redesign of berthing spaces involves removal of wooden piers and replacement with concrete successors that will be optimally oriented and spaced so as to minimize reported difficulties of achieving ingress by nuclear submarines, without vitiating the constraints imposed by servicing requirements.

To be sure, waterfront design is essentially an engineering problem, and if the Thames River were a static fluid environment, it would be a fairly straightforward problem. However, submarines attempting to "land" at assigned berths must first navigate the channel where tidal effects generate ebb and flow of currents which, coupled with the submarine's low forward speed, often complicates landing and may even make it a hazardous undertaking. Since it is not feasible to modify either the environment or the submarine, it is quite logical to examine the possibility that alteration of the waterfront layout will produce beneficial effects upon the berthing operation.

The objective of the study undertaken by OCEANICS, Inc. is to determine the optimum pier orientation and slip width for ease of berthing, such information to be potential input to final engineering design. In the first instant, there are no restrictions on the solution other than environmental factors that affect the handling characteristics of nuclear submarines. Thus, at the outset, considerable latitude exists in optimizing orientation and width of slips even to the extent of introducing berthing concepts that depart radically from the present waterfront arrangement which is shown in the frontispiece. However, it would be naive, if not wasteful, to completely ignore the practical aspects of the situation. Such factors as: cost, prescribed minimum number of berths, servicing requirements, and existing permanent piers, must certainly be considered.

In order to develop a realistic approach to the problem, the first step was to acquire an understanding of all its aspects and this necessitated the gathering and evaluation of data and information pertinent to the problem. When the environmental, operational, logistic, and practical factors were considered collectively, possible alternative solutions were revealed. These solutions comprised: 1) changes in slip width and orientation of piers with respect to present design, 2) development of a "sawtooth" berthing arrangement, 3) combinations of these two solutions.

The problem was subsequently reformulated to comprise study of the spatial requirements for landing of tug-assisted SSN and SSBN-type submarines, for conditions 1) and 2) above, in a variety of currents, and for consideration of multiple berthing. The mechanism for evaluating the effects of proposed variations in layout is a computer experiment that simulates submarine landing for the specified conditions. The end result is an estimate of optimum spacing and orientation of piers as regards the two basic types of solutions mentioned above.

This report describes the way in which the study was developed and carried out and the results that were obtained. From the conclusions, recommendations for implementation are given that will hopefully be useful in final redesign of the waterfront at the New London Submarine Base.

COLLECTION OF DATA AND BASIC INFORMATION

Initially, the problem was defined in terms of easing the berthing difficulties of two classes of nuclear submarines (SSN 637, SSBN 616), by studying their maneuvering characteristics in different environmental conditions [1].* In this way, it would be possible to determine the optimum pier angle for ingress and egress and to optimize the distance between piers for single or multiple berthing. However, it was

*See list of REFERENCES at end of text.

recognized that the submarine could not be treated as a system independent of the human hand that guided it. In fact, the notion that a landing problem exists was inspired by the operator; it follows that solution of the problem must necessarily satisfy the operator. Consequently, the first step was to not only collect whatever data was available on the oceanographic environment and on the handling characteristics of the submarines involved, but to extract and assemble pertinent information from all those people connected with the operation so that the nature of the problem could be clearly defined. In these endeavors, personnel of the Naval Facilities Engineering Command were most helpful. Their assistance in arranging for key interviews at the submarine base has resulted in identification of the parameters involved so that a meaningful solution could be sought.

The interviews, although limited in number, were most productive, because different points of view were expressed by such people as: submarine captains and crews, tugboat operators, public works officials, logistics support personnel, and the base commander. In addition, OCEANICS personnel were permitted to observe a nuclear submarine landing (USS TINOSA, SSN 606) and this was most instructive.

The following is a distillation of all the general information and data that was collected.

Environmental Factors

The current tables published by the Department of Commerce [2] and recent Coast and Geodetic Survey observations [3] indicate that the current in the Thames channel rarely exceeds one kt, except during spring freshets when an ebb current of 3 kts is not uncommon. In addition, nuclear submarines are now almost always landed in slack water which suggests that current effects should be minimal. Nevertheless, there was a general displeasure, voiced by the submarine and tugboat operators, regarding the currents which, it was claimed, plagued them almost constantly. It seems that even the trace of a current tends to complicate a berthing operation which requires the submarine to turn beam-to the channel axis, in order to achieve ingress. Furthermore, the present restriction to slack-water landing is an operational choice of convenience, not a requirement. In fact, it has been established that solution of the problem should encompass channel navigation at any time. Hence, the effect of current is potentially more significant than even considered initially.

It was the general opinion of the submarine and tugboat operators that: 1) the currents encountered were of greater magnitude than the published tables indicated, 2) whatever currents were there made landings difficult, 3) any berthing arrangement that would eliminate current on the beam, upon approaching the berth, would be beneficial, 4) fog, wind, and channel traffic are secondary hazards that do not evoke too much concern, and 5) daylight and tide are routine operational constraints.

Operational Factors

The handling of a nuclear submarine to gain ingress at any of the piers is an intricate maneuver that is always tug-attended and often tug-assisted. To obtain first-hand knowledge of just what is involved in berthing a nuclear submarine, the landing of the USS TIROSA (SSN 606) was witnessed from one of the assisting tugs and from the berthing pier. Two tugs were involved; one moored at the bow of the submarine, the other standing by because it could not successfully negotiate a mooring at the stern. The landing, on the south side of pier 13, was skillfully supervised by a junior officer under the watchful eye of the captain. However, it was made clear that that particular landing was the exception rather than the rule, since there was absolutely no discernible current present. We were assured that the nickname "Ulcer Gulch" for the Thames channel was not to be taken lightly. Subsequently, a meeting was held with the captain and his staff and additional information on berthing was obtained.

It appears that backing out of a berth is not a major operational factor, because tugs are always available to provide lateral restraint (which is a problem) and to assist in turning. The approach to the berth is accomplished by the submarine which, in effect, carries the tug(s) along. Depending on the current flow and the side of the pier assigned, the tug may or may not be called upon for assistance. In the case of the TINOSA, the tug was used in mid-turn to provide an extra kick to bring the submarine about.

From the preceding observations, which were acknowledged in the interviews, it appears that submarine berthing is an art that depends upon the skill of the handler, his knowledge of the ship, assessment of channel conditions, and ability to employ the tugs affectively. In general, it was ascertained that no two officers follow the same landing pattern and that, in fact, the same officer would not be likely to land the same way twice in succession, because the environment was never precisely the same. Elimination of the effect of channel current was hailed as the greatest potential relief to the landing problem.

In a more practical vein, it was mentioned by one captain that a modicum of improvement could be achieved by the simple expedient of tapering the ends of the slips. Even a few more feet of clearance at the entrance to the berth would be welcome. All those interviewed asked for more space between slips and the base commander simply suggested removal of every other pier. There was no particular enthusiasm for nesting submarines, even if more space were provided.

The possibility of berthing parallel to the current was well received and led to one suggestion that the most desirable landing would involve tying up to a structure in mid-stream and then automatic berthing achieved by a round-house-like system of tracks. Although such a solution is not practical, it became clear that operating personnel take berthing quite seriously and have given thought to means of alleviating the difficulties of this aspect of submarine handling.

Coincident with the interviews, a survey was made of existing data on submarine maneuvering and/or analytical methods of assessing handling on the surface. The search covered work done at the David Taylor Model Basin, the Naval Training Devices Center, Stevens Institute of Technology and the open literature. It appears that very little has been done in this area of operation and this is due, for the most part, to the enormous variability in the handling skill of the man in charge. In addition to the human factor, the arbitrary use of "instant power" from a tug makes it even more difficult to assess precisely submarine maneuverability in the Thames channel.

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Finally, there was general agreement that small changes in slip angle would probably not materially affect landing, so long as the current still plagued the submarine. Moreover, since the current reversed direction periodically, it was not obvious that the present orientation was optimum particularly for nuclear submarines.

Logistic and Practical Factors

The very first set of interviews provided a somewhat better grasp of what the submarine was up against and suggested a new tack to the investigation. Since there was an apparent problem in berthing, it was decided to provide the interviewees with alternative solutions that might be appealing. On the other hand, the cure might be worse than the disease and this knowledge could act as good counsel for the proposed renovations [4] now being considered.

Consequently, several new design concepts were evolved that took no account of the Navy's thinking in the matter nor even that piers 10, 12 and 13 were already permanently installed, and that pier 6 was presently scheduled for replacement. These designs are shown in Figures 1 - 4 and the single principle which guided their conception was avoidance of current on the beam by providing ingress parallel to the channel.

Figures 1 and 2 are basically the same, showing stall berthing, in one case single, in the other multiple; Figures 3 and 4 are also basically the same, showing sawtooth berthing with more berths provided in Figure 3. The stall berthing concept may also be viewed as extending only south of pier 10, in deference to the existing concrete piers.

The tugboat operators were not impressed with the limited maneuvering room in the stall-berthing designs. Furthermore, the officer responsible for supplying services was quite unhappy with the stall-berthing idea, in general, because an entire pier (with as many as a dozen submarines tied up) would be incapacitated whenever nuclear weapons or liquid oxygen was handled. Also, it was noted that a mass evacuation would be chaotic. The stall berthing in Figure 2 was even more objectionable, because the nested submarines would have to be serviced over the bow and this was considered to be virtually impossible. However, it was conceded that landing in the stall berthing of Figure 1 would be desirable if the bay were widened, if more space were provided between slips and if the servicing and traffic requirements could be met.

The sawooth berthing concepts, shown in Figures 3 and 4, were also greeted with mixed reactions. There were some qualms about threading a channel lined with submarines although the objection waned somewhat when it was proposed to increase the distance between the quay wall and the "island".

To answer the objection that loading of nuclear weapons or liquid oxygen could tie up the whole "island", a second bridge, at the opposite end (Figure 4) was proposed. However, the notion of one bridge, let alone two, brought a chilly response from the Public Works Department. In general, sawtooth berthing on the quay wall was well received; addition of the island was not.

As a compromise, consider Figure 5 which shows multiple sawtooth berthing on the quay wall. The problem of current effects is greatly reduced and the logistics of servicing does not appear to be violated. In the space now occupied by piers 1 - 8, ten nuclear submarines could be berthed; this appears to satisfy future requirements for such spaces [4].

FORMULATION OF PROBLEM

The problem of berthing nuclear submarines at the New London Submarine Base was initially conceived, for the purposes of this study, as oceanographic-hydrodynamic in nature. However, when operational, logistic, and engineering constraints were brought into proper perspective, it was determined that the originally proposed procedure could be improved to provide a practical and useful solution to the problem.

The basis for the approach used in this study was the collected impression obtained from evaluation of all the information garnered on the problem and presented in the previous section. As might be expected, there was some variation in the personal opinions of individuals regarding the importance of particular aspects. However, there was unanimity on the key elements of the problem and, coupled with the environmental data, the following conclusions on the nature of the problem were drawn.

1. Environmental factors such as: current, wind, fog, rain, traffic, tide, and channel geometry all influence the way in which a nuclear submarine is landed. Current is considered to be the single most important adversary and makes tug attendance mandatory and serious damage a definite possibility. This problem exists despite the fact that all nuclear submarine landings are virtually restricted to slack water and daylight hours. If there were no current whatsoever, the other environmental factors probably would be rated as no more than nuisances. The condition that nuclear submarines, in the future, will be required to land during any stage of current ebb or flood will magnify the problem considerably.

2. Since the primary current is tidal in nature, and therefore reverses itself, there should be little choice between berthing on the north or south side of any pier. However, due to present pier orientation, a south-side

landing is generally preferred. This reinforces the notion that present pier orientation is not optimum.

3. Egress is not a significant problem for nuclear submarines, as long as tug assistance is available for lateral restraint.

4. Although every landing is different, one may usually assume that, with respect to the present pier orientation, the submarine is aligned parallel to the axis of the pier, upon approach. It is displaced, either north or south of the pier, depending on current direction, and a distance depending upon human judgment of the drift rate. The tugs are quite efficient in turning the submarine but are not as effective in changing the lateral inertia due to the current. Consequently, small changes in pier orientation will not materially alter the lateral force component of the current and therefore do little to ease landing difficulty. On the other hand, large changes in slip orientation, such as recommended in the saw-tooth concept (Figures 3 - 5) would permit ingress nearly parallel to the current and are likely to result in considerable relaxation of the difficulties that arise when even a small component of the current is on the beam.

5. If radical redesign is not feasible, a first order of improvement can be achieved by arbitrarily increasing slip width and by tapering the ends of piers to provide additional clearance, or, at least, buffering the pier ends.

From the foregoing, a case has been presented for redesign of the waterfront, according to the sawtooth concept, as a means of berthing nuclear submarines more easily and safely. Figure 5 shows the kind of arrangement that is likely to be effective. Because of the expected ease of landing in this case, multiple berthing is considered to be feasible.

It should be understood that Figure 5 is conceptual and implies no recommendation for final engineering design as regards location, dimensions, or extent of the sawtooth. The layout as shown does, however, recognize that major alteration above pier 9 is undesirable. Furthermore, as arranged, there would be room for 10 nuclear submarines, and this satisfies the requirement for 9 such berths [4]. There seems to be no obvious objection to the sawtooth from a servicing viewpoint and, with respect to construction, it may conceivably be less costly than "conventional" piers.

In order to verify these preliminary conclusions, a comprehensive computer-simulation experiment was undertaken. The objectives of the experiment are to determine the optimum slip width and pier orientation, for the conventional arrangement, and to evaluate the effectiveness of the sawtooth arrangement in achieving a landing.

For the purpose of experimentation, both SSN and SSBN submarine forms were considered. The experimental parameters included: current magnitude and direction, pier orientation, and initial forward speed of the submarine. Variables applied subjectively were: rudder angle, to maintain submarine heading; tug power, to minimize trajectory drift; and ship power to change forward speed. In the following sections, the computer experiment is described in detail and the results are discussed and final conclusions and recommendations are given.

DEVELOPMENT OF COMPUTER EXPERIMENT

Before discussing the details of the computer simulation of submarine docking, it is essential to outline the various hydrodynamic and structural characteristics of nuclear submarines as well as standard fleet-type submarines. Nuclear submarines of the SSN and SSBN classes are slender streamlined forms, with almost circular sections in the main hull envelope (except for appendages such as the sail, the missile deck, etc.), and they are single-screw vessels, with the propeller located aft of the horizontal and vertical stabilizing surfaces. In addition, highly sophisticated and fragile sonar gear is located on the ship hull in the bow region, and care must be taken to avoid any damage to such equipment by impacts or other damaging actions, as loss of sonar capability will severely limit the military effectiveness of the submarine.

The single-screw property of the nuclear submarine is the most significant feature that affects the submarine's maneuvering capability at low forward speeds, in contrast to fleet-type submarines which are twin-screw ships. The stabilizing surfaces, the rudders, etc. on fleet-type submarines are usually located aft of the propellers, so that these control surfaces are in the propeller race, thereby providing an augmentation of the local flow velocity past the control surfaces and hence an increased control force. Another feature of the twin-screw installation is the ability to separately control the thrust of each screw, so that longitudinal forces in opposite directions can be generated by the screws, which then results in a yawing moment. Thus, a twin-screw fleet-type boat can "twist" itself around without any external vehicle providing assistance; its heading is therefore directly controllable by the submarine itself by virtue of the two effects described above. In direct contrast to this, the single screw nuclear submarine cannot use longitudinal thrust from the propeller to achieve any significant heading change, so that the rudder control effectiveness is only dependent on the forward speed, with a slight influence of the local propeller-induced velocity field. From the foregoing discussion, it is easy to see the need for tug assistance when landing a nuclear submarine in the presence of a large environmental disturbance such as a current, and with the attendant requirement for low forward speed.

Within the framework of the capabilities of nuclear submarines, as described above, a computer simulation study was carried out in order to verify these qualitative characteristics of nuclear submarine maneuverability in the landing operation, and to apply the various control inputs necessary to achieve a successful landing in the face of various disturbances due to currents. The required inputs, their effects on the submarine trajectory, and the significance of such behavior in terms of pier orientation and spacing are found from this method of simulation, and the methods, assumptions, etc. used in that phase of work are described in the following.

Conditions for Solution of Problem

In seeking a solution by means of computer simulation, certain assumptions are made initially as to the nature of the environment and the properties of auxiliary systems such as the tugs. Geometrical and kinematic restrictions are also considered, in a study of this type, and the particular numerical values are selected as representative for the purposes of the particular mathematical analysis and simulation.

For this study, it was assumed that the current direction was parallel to the shoreline and that the magnitudes of the currents extended to a maximum of 3 kts for ebb currents and 2 kts for flood currents. The submarine is assumed to be traveling initially at a forward speed of 3 kts just after it makes its turn from the middle of the channel and starts to head towards one of the presently existing piers. The location of the submarine is assumed to be at a distance corresponding to one body length from the end of the pier where this turn is made, and that instant corresponds to time zero in the computer run.

The current is assumed to be uniform over the entire extent of the channel (i.e constant magnitude), but it is assumed that "quiescent" water exists between the piers and that the submarine no longer "feels" the current from the time that the submarine CG reaches the end of the pier until a final landing is achieved. However, whatever velocity the submarine has at the instant it reaches this "quiescent" water region will remain as essentially an "initial condition" for the computations while the submarine is within the confines of two adjacent piers. This transition between "current present" and "no current" is only considered in analyzing conditions appropriate to the presently existing pier system, and it is not applied when considering the sawtooth pier design, although the sawtooth may also have a mitigating effect on the current in certain cases.

When considering the sawtooth pier configuration, the submarine forward speed is different from that assumed for the conventional pier landing case. For an ebb current, the initial submarine forward speed is assumed to be such that a net ground speed of 3 kts is achieved, and hence a relatively larger forward speed is selected for the submarine itself relative to its own inertial reference frame. For example, in a 2 kt ebb current, the submarine will have an effective speed of 5 kts in its own reference frame. Similarly, in a flood current, the same net ground speed of 3 kts is assumed for the initial ship speed condition, corresponding to a relatively low forward speed to be maintained by the submarine in its own reference frame.

In carrying out the computer simulation, a run is terminated when the net vector velocity of the submarine is less than 0.20 ft./sec., so that the ship is effectively brought to rest and avoids any impacts with the piers in the terminal state. Another operational constraint incorporated in this computer study is an allowance for a 15 second time delay for attaining the final steady state propeller thrust of the submarine following an engine order for change of propeller rpm. This change in thrust is brought about continuously during the 15 second time period to provide a realistic measure of continuity in force development. The tug thrust changes are assumed to occur almost instantaneously, in comparison to ship power changes, and hence no time delay is considered for application of tug forces to the submarine.

With regard to the tug force characteristics, some information concerning the present tugs at the New London Submarine Base was obtained during discussion with the tugboat operators. The specific information received included physical dimensions of the two different tugs, displacements, shaft horsepower, etc. and from this data a single composite tug characteristic was derived. Assumption of an average SHP of 900 HP at a maximum speed of 12 kts, and allowance for the thrust deduction factor and an approximate ratio between EHP and SHP, resulted in a value of 19,400 lb. of thrust as a maximum for each tug. With propeller thrust taken proportional to $(rpm)^2$, the thrust force developed at the "$\frac{2}{3}$ bell" was estimated to be 14,900 lb. and 7,500 lb. at the "$\frac{1}{3}$ bell", with the same magnitudes assumed to apply for both forward and reverse conditions. These estimates are expected to be of the correct order of magnitude and hence directly applicable in the present simulation study.

When considering power, thrust, etc. for the nuclear submarines, it was assumed that the same basic nuclear powerplant was installed in each type of submarine (SSN or SSBN). Thus it is to be expected that reversing the propeller on an SSBN submarine will be somewhat less effective in reducing the submarine forward speed, as compared to the SSN case, because of the larger mass of the SSBN submarines.

Although SSBN submarines are considered in this study, there is presently no plan for berthing such submarines at the New London Submarine Base. However, in the interest of long range planning for expanded utilization of the base, this class of nuclear submarine is included.

Within the computer simulation study, no effects of wind are considered, since there is very little exposed surface of the submarine and no significant force is developed from such a relatively low density fluid. Another environmental factor, i.e. the possibility of eddying flow near the pier ends and/or within the pier spaces, has been neglected in this study due to lack of precise information on such flow characteristics.

Mathematical Simulation of Submarine Response

In order to simulate mathematically the trajectory of a submarine in the docking maneuver, it is necessary to have an appropriate set of equations of motion. These equations must provide for: varying forward speed, propeller force alteration, effects of externally applied forces by means of tugs, etc. Since low forward speed is necessary in this case, the usual form of ship motion equations [5], which is based on linearizing various motion perturbations relative to a large constant forward speed, is not applicable. An allowance for significant nonlinear hydrodynamic force and moment terms must be made, and values of the applicable numerical coefficients determined by estimates based on theoretical guidance or from model experiments. A fortunate set of circumstances allowed use of model test data, together with an equation formulation obtained from such data, which was originally prepared for development of a training device [6]. The model tested was not precisely identified as corresponding to any particular nuclear submarine class, but was representative of a general modern attack-type nuclear submarine. Accordingly, the data presented in [6] was used to represent the physical and the hydrodynamic characteristics of SSN submarines in this study. The equations, which are based on a mathematical fit of the hydrodynamic force and moment data obtained in the model experiments of [6], are also directly adapted and applied in the present investigation.

The axis system and reference frames are chosen similar to that in [6], with an inertial frame chosen in the fluid and moving with the constant current; this fluid frame in turn is parallel to the fixed inertial reference frame which is fixed at some point on the "ground". Thus, resultant velocities with respect to the "ground" are determined by vector addition of components, and the time integrals of these velocities give the actual space trajectories of the submarine relative to the fixed inertial reference frame. The particular fixed inertial reference frame chosen for this study is shown in Figure 6, where the origin of coordinates is taken to be the desired location of the submarine CG relative to the pier, i.e. the final destination point assuming a perfect landing.

The equations of motion of the submarine (with respect to body axes) are expressed in terms of the variables u, v and r, which represent the axial velocity (u) of the submarine along its longitudinal axis; the lateral velocity (v) along a direction perpendicular to the longitudinal axis of the submarine; and the angular velocity (r) about an axis normal to the plane of the water surface and the ship axes. The yaw angle ψ is given by

$$\psi = \int_0^t r \, dt + \psi(0) \qquad (1)$$

Using the notation outlined in [6], the equations of motion are expressed below, for the case where the ship axial speed is 3 kts or less. In some of the cases for the sawtooth-pier design, the axial velocity exceeds 3 kts; the same equations are assumed to be applicable. The equations are:

Longitudinal Force Equation

$$(m - X_{\dot{u}})\dot{u} = X_1 u + X_2 u|u| + X_3 v^2 + X_4 vr + \left[X_{\delta\delta}(u)\right]\delta^2 + X_E(u) + X_T \quad (2)$$

Lateral Force Equation

$$(m - K_{Dm} Y_{\dot{v}})\dot{v} = K_D\left[Y_1 ur + Y_7 v\left(|v| + \sqrt{u^2 + v^2}\right)\right] + Y(u,\delta) + Y_E + Y_T \quad (3)$$

Yaw Moment Equation

$$(I_{zz} - K_{Dm} N_{\dot{r}})\dot{r} = K_D\left[N_7 r|r| + v\left(N_8\sqrt{u^2 + v^2} + N_9|r| + N_{10}u + N_{11}\frac{v^2 u}{\sqrt{u^2 + v^2}}\right)\right] + N(u,\delta) + N_E + N_T \quad (4)$$

where m is the submarine mass; K_{Dm} is an added mass correction factor to account for shallow water influence; K_D is a factor that modifies the quasi-steady hydrodynamic force terms to account for the influence of shallow water depth; δ represents the rudder angle; the terms with E subscripts represent the respective force or moment due to propeller action in response to an engine order; terms with a T subscript represent the respective force or moment due to the tugs; $Y(u,\delta)$ and $N(u,\delta)$ are the lateral force and yaw moment contributions due to the rudder; and the various coefficients of quasi-steady hydrodynamic forces such as X_1, Y_7, etc. are identified with specific numerical subscripts, which are in turn defined in terms of the submarine characteristic lengths, dimensionless hydrodynamic stability derivatives, etc. in [6].

The forces and moments due to rudder deflection and to propeller action are dependent upon the engine order, which corresponds to discrete propeller rpm values and produces a precise forward speed. In the present simulation study it is assumed that at time t = 0 the submarine is moving forward at a specific constant forward speed, which in most cases considered herein is 3 kts. No concern is given as to how the submarine arrived at that particular speed prior to that time, and it is assumed that the engine and propeller are stopped at t = 0. The submarine is assumed to move ahead and its speed is slightly affected by certain hydrodynamic forces, but the predominant influence on the forward speed is the longitudinal force due to the propeller when reverse engine orders such as "back one-third" (denoted as $E_{-\frac{1}{3}}$) or "back two-thirds" (denoted as $E_{-\frac{2}{3}}$) are commanded, resulting in a continous reduction of forward speed following the application of the appropriate propeller action.

For the case of zero or "back" engine orders all of the rudder force and moment terms have no dependence in form on the precise engine order. Thus we have the following representations for E_{-0}, $E_{\frac{1}{3}}$, and $E_{\frac{2}{3}}$:

$$X_{\delta\delta} = -0.88 - 0.216u - 0.057u^2 \tag{5}$$

$$Y(u,\delta) = (8.1\delta - 0.0024\delta^3)u^2 \tag{6}$$

$$N(u,\delta) = (-1,210\delta + 0.517\delta^3)u^2 \tag{7}$$

where δ is measured in degrees. The direct propeller force and moment terms are

$$X_{E_{-0}} = -17.5u^2 \tag{8}$$

$$X_{E_{\frac{1}{3}}} = -14,700 - 150.6u + 92.9u^2 - 5.45u^3 \tag{9}$$

$$X_{E_{\frac{2}{3}}} = -33,850 - 1,448u + 37.9u^2 + 2.57u^3 \tag{10}$$

$$Y_{E_{-0}} = Y_{E_{\frac{1}{3}}} = N_{E_{-0}} = N_{E_{\frac{1}{3}}} = 0 \tag{11}$$

$$Y_{E_{\frac{2}{3}}} = -330(\delta + 5) + 6.85(\delta + 5)|\delta + 5| \tag{12}$$

$$N_{E_{\frac{2}{3}}} = 51,470(\delta + 5) - 850(\delta + 5)|\delta + 5| \tag{13}$$

with δ measured in degrees in Equations (12) and (13). It can be seen that there is a small negative Y-force and a small positive yawing moment (for $\delta > -5^{\circ}$) as a result of propeller action in the $-\frac{2}{3}$ engine command mode, thereby possibly assisting a port landing (the port side of the submarine in contact with the pier).

As far as tug forces are concerned, the tug thrust values are $\pm$7,500 lb. in the $\pm\frac{1}{3}$ engine order of the tug and $\pm$14,900 lb. in the $\pm\frac{2}{3}$ engine order of the tug, as discussed in the previous section. The forces applied to the submarine depend upon the attitudes and locations of the tugs relative to the submarine when they are in contact and tug action is commanded. To account for the additional resistance force of the tugs, an increment of approximately 20% of the submarine hull force in the axial direction is added so that

$$X_T = 0.2\left(X_1 u + X_2 u|u| + X_3 v^2 + X_4 vr \right) + X_{E_T}$$

where X_{E_T} represents the tug force in the axial direction of the submarine according to the tug engine orders, as well as the orientation of the tugs relative to the submarine. The lateral force due to the tugs depends upon the engine order and the orientation of the tugs relative to the submarine, with a maximum lateral force of almost 30,000 lb. being available for moving the submarine sideways. Similarly the yaw moment due to the tug is also determined by engine order and orientation of the tug, but it is also affected significantly by the locations of the tugs since these locations determine the moment arms. Maximum distances of 120 ft.

from the submarine CG (origin of body axis coordinate system) were allowed in this study.

The numerical values of various coefficients used in this study for the SSN submarine are given below:

$m = 272 \times 10^3$; $I_{zz} = 1.33 \times 10^9$; $K_{Dm} = 1.13$; $K_D = 4.5$;

$X_{\dot{u}} = -8.98 \times 10^3$; $X_1 = -36$; $X_2 = -60.7$; $X_3 = 204$;

$X_4 = 455 \times 10^3$; $Y_{\dot{v}} = -255 \times 10^3$; $Y_1 = -156.7 \times 10^3$;

$Y_7 = -3.17 \times 10^3$; $N_{\dot{r}} = -8.12 \times 10^8$; $N_7 = -152 \times 10^9$;

$N_8 = -257 \times 10^3$; $N_9 = -204 \times 10^3$; $N_{10} = -165 \times 10^3$;

$N_{11} = -148 \times 10^3$;

with all dimensions in the pound-foot-second unit systems. Values of other hydrodynamic coefficients due to the rudder and the propeller have been presented for the SSN submarine in Equations (5) - (13).

All of the numerical values presented above were obtained from the results of model experiments [6] performed on a representative SSN submarine model. No information was obtained or presented in [6] for the SSBN submarines, but values were found for use in the present investigation by "scaling" the values outlined above so that they become representative of the true values. The mass and moment of inertia in yaw are simply found from knowledge of the displacement and length of SSBN-616 class submarines. Since the same nuclear propulsion plant is assumed for each class of nuclear submarine, the forces due to propeller action are the same as given in Equations (8) - (13) for the SSN submarines. The added mass and hull hydrodynamic force factors K_{Dm} and K_D due to shallow water effects are the same for the SSBN as for the SSN, since the drafts and local water depths are the same in each case. The added mass terms $X_{\dot{u}}$, $Y_{\dot{v}}$ and $N_{\dot{r}}$ for the SSBN were determined by assuming the same ratio to the actual body mass as in the SSN case. The various hydrodynamic terms were assumed to contain the same dimensionless stability derivative values for each type of submarine, but the values of the coefficients in the equations were increased by appropriate powers of the ratios of the vessel lengths, where this ratio is denoted as λ. Thus the quantities X_1, X_2, the hydrodynamic part of X_4, Y_1, Y_7, and N_{11} were scaled up by λ^2, while X_3 is increased by the factor λ. The quantities N_8, N_9, and N_{10} were scaled up by the factor λ^3, and N_7 was increased by the quantity λ^5. The rudder contribution to the longitudinal and lateral forces remained the same, while the yaw moment rudder term was increased by the factor λ (with λ=1.5 in this study) to account for the larger moment arm. The basic coefficient values used in studying the SSBN submarines are listed in the following:

$m = 637 \times 10^3$; $I_{zz} = 6.1 \times 10^9$; $K_{Dm} = 1.13$; $K_D = 4.5$;

$X_{\dot{u}} = -21 \times 10^3$; $X_1 = -82.9$; $X_2 = -140$; $X_3 = 310$; $X_4 = 105 \times 10^4$;

$Y_{\dot{v}} = -597 \times 10^3$; $Y_1 = -360 \times 10^3$; $Y_7 = -7.3 \times 10^3$;
$N_r = -3.72 \times 10^9$; $N_7 = -12 \times 10^{11}$; $N_8 = -9 \times 10^5$;
$N_9 = -72 \times 10^4$; $N_{10} = -5.8 \times 10^5$; $N_{11} = -340 \times 10^3$;

with the same system of units as for the SSN case.

The equations were programmed for solution on a PDP-8 digital computer with a numerical scheme using an integration time (that was varied in each problem considered) ranging from 0.25 sec. to 1.0 sec. Printout of answers for final trajectory, velocities, etc. was also variable for each problem, being either every 10 sec. or every 20 sec. The program was formulated with certain decision-making capability so that an "interrupt" signal could be introduced in order to allow for imposed inputs such as rudder deflection (limited to a rate of 6°/sec. in the computation); engine commands and resultant propeller forces; and application of tug forces, as well as changes in these inputs at various times during the course of a problem solution.

<u>Computer Results</u>

Before computer production runs, for simulation of submarine docking in various currents with different pier arrangements were carried out, certain basic computer experiments were run to illustrate fundamental phenomena that occur during such low speed maneuvers. For a pier system normal to the shoreline ($\alpha = 0$ in Figure 6), it was found that the submarine experiences very little forward speed reduction due to the pure hull hydrodynamic forces when it is initially at a 3-kt forward speed. Speed reduction was achieved by use of propeller "backing", where a retarding force is applied continuously over a 15-second time interval until maximum build-up of force is attained. The submarine experiences a constant deceleration after the force is fully effective, and the time for stopping, as well as the distance traveled, are easily estimated by simple particle dynamics relations. These estimates compared well with the actual computer responses (within 10 seconds of actual time), so it was concluded that propeller thrust alteration has the greatest effect on forward speed and distance traveled, and that the time for applying backing commands to the submarine propeller can be judged easily during a computation in order to achieve the required stopping distance and positioning.

Another experimental finding was that the rudder was essentially ineffective in achieving any significant course change of the submarine at 3 kts forward speed, when considering the time and distance requirements for docking subsequent to the conditions at time $t = 0$ (submarine bow located one body length from the outer end of the pier). Yaw angle changes of about 5° were found due to rudder deflection for cross-current docking conditions, and even in that case it may cause difficulties because the ship's turning motion must be halted in order to arrive at a successful docking. Thus, rudder action was not used in these standard docking simulations, and the submarine essentially maintains its initial heading, disregarding hull hydrodynamic forces, until a large enough yaw moment, such as that due to tugs, is applied. In the case of the sawtooth pier arrangement, the longer time of travel and, in the case of ebb currents, the larger submarine forward speed permits greater influence on control to be achieved by application of the rudder.

The method of analysis used in this study considers the steady current to produce a drifting component of the submarine in the direction of the current. With little lateral body velocity of the submarine itself, together with the almost constant forward speed of the submarine for most of its cross-river motion, the submarine trajectory is essentially geometrically determined. Thus, the submarine trajectory can be estimated fairly well for most of its length across the river, with the only important deviations occurring due to reversing the submarine propeller and/or applying forces and moments via the tugs. As an example, considering a pier normal to the shoreline, the location of the initial point (at t = 0) is estimated by assuming, for the case of a 1-kt ebb current and 3-kt forward speed, that the submarine trajectory will be primarily at an angle of about 18^{o} (i.e. $\tan^{-1} \frac{1}{3}$) with respect to the pier orientation. The heading of the ship is selected parallel to the dock, and the required clearance of the bow then provides the necessary information for selecting the initial upstream (for ebb current) location for the start of the docking maneuver trajectory.

All of these simple results were obtained from various computer experimental runs. They verified some of our original concepts and, in addition, provided insight into the important physical phenomena that influence this particular problem. Detailed solutions for a number of particular cases comprising: pier arrangements oriented normal to the shoreline, at angles a up to 45^{o} from the shoreline, and for the proposed sawtooth arrangement, are discussed in the next section of the report. Solutions were obtained for currents, both ebb and flood, ranging from 0.5 kts to 3 kts, for both SSN and SSBN type submarines, with consideration of both port and starboard landings. The results are presented in graph form in Figures 7 - 29, with sufficient explanation on each graph to illustrate: environmental conditions; control action via rudder, propeller, or tug; submarine orientation and clearances; space requirements; etc. Discussion of these results, together with an interpretation of their implications in regard to future construction of the submarine base waterfront, are presented in the following sections.

DISCUSSION OF RESULTS

The following discussion relates to the results achieved by computer simulation of nuclear submarine landing trajectories. The conclusions that follow are based upon all the results obtained and not necessarily upon the particular trajectories that are included in the discussion for illustrative purposes.

Figures 7 - 15 show selected computer trajectories for the SSN-type nuclear submarine. In each case, the pier was perpendicular to the axis of the channel and the drift rate due to current was countered by application of tug and/or ship power, as appropriate, to affect a landing. Because the submarine is initially oriented perpendicular to the current (and channel axis), the resulting symmetry does not distinguish between ebb and flood currents. That is, an ebb current would have the same effect on a landing south of the pier as the same flood current would have on a landing north of the pier. Thus, the two trajectories would be the same. For simplicity of discussion, the absolute direction of the current is discarded and the landing is referred to as either starboard (when that side of the submarine is against the pier) or port.

A current of 1/2 kt resulted in the trajectories shown in Figures 7 and 8. In the port landing (Figure 7), the tugs were used to slow the submarine and counter the current. In the starboard landing (Figure 8), ship power was used to reduce forward speed, while the tugs retarded drift. The difference in the two trajectories is due to the requirement that the submarine clear the pier in the port landing and then reverse direction to achieve the landing. The minimum space required for landing in the port case (Figure 7) comprises the distance from the pier to the furthest point on the trajectory plus half the beam of the submarine plus the space occupied by the tugs. If tug space is estimated at about 100 feet, the line to the right of the trajectory maximum represents the distance occupied by the submarine-tugboat system during landing. In this case, the space required is about 160 feet which is just about what is needed under present conditions.

In the case of the starboard landing (Figure 8), it is required to clear the pier on the left (not shown). Thus, the position of the submarine when its bow reaches the end of the pier is the appropriate place to estimate the space occupied by the submarine-tugboat system, about

160 feet, as shown in Figure 8.

From Figures 7 and 8, it is seen that the space required to land SSN-type nuclear submarines, in a 0.5-kt current, is not much less than is presently available. Indeed, if another submarine were already berthed in the slip at the opposite pier, landing would be quite difficult, because the tugs could not freely be oriented perpendicular to the submarine, if desired.

The situation just described, as simulated for a 0.5-kt current, appears to represent what might be expected in what is known as a "slack water" landing, under present operating conditions. The results suggest that currents up to 0.5 kts will tax the efficacy of the present slip width, for the purpose of berthing nuclear submarines.

When the current is increased to 1 kt, the landing becomes considerably more difficult. Figure 9 shows a port landing where submarine power was utilized ($E\frac{1}{3}$ at the *) to reduce forward speed to zero, at the moment of landing, while the tugs were oriented perpendicular to the submarine to obtain maximum reduction of current drift force. In Figure 10, no submarine power was utilized, but the tugs were angled at 20° to the horizontal, in order to slow the submarine and to change trajectory. It is clear from Figures 9 and 10 that the use of tugs alone to produce both lateral and longitudinal forces results in a much larger space requirement.

For the 1-kt starboard landing (Figure 11), both tug and submarine power are used, and it is seen that the space requirement is about the same as for the port landing (Figure 9). In general, a reasonably good landing would require about 185 feet of space, while a poor landing (Figure 10) could take as much as 230 feet.

With a current of 2 kts, it is mandatory to utilize both tug and ship power and as seen in Figures 12 and 13, it becomes increasingly difficult to overcome the current. Figures 14 and 15 show the effects of a 3-kt current and it is quite clear that it would be impossible to berth one such nuclear submarine, let alone two or more in the same slip, unless considerable space is provided.

From the results of the experiments on perpendicular piers, it appears that the current imparts considerable lateral momentum to the submarine. In fact, for 2- and 3-kt currents, the submarine is almost unmanageable; the slip-width requirements are prohibitive. However, except for spring freshets, currents above 1 kt are expected to be uncommon. Therefore, it is reasonable to consider the space needed for the 1-kt condition as a possible design criterion.

From the results of Figures 9 and 11, it was found that for the conditions tested, a space of 185 feet was required, for generally good landings. If 200 feet is accepted as a basic figure that includes some poor landings, then 250 feet would be an appropriate slip width if another submarine were already berthed at the adjacent pier, and to include a third submarine (nesting), 285 feet is considered to be the appropriate slip width.

The estimated slip width requirements, for different imposed currents, in the perpendicular-pier case are summarized in Table I.

Table I. Estimated Slip Widths Required for Berthing Nuclear Submarines in Perpendicular Pier Orientation

	SSN				SSBN		
Current (kts)	0.5	1.0	2.0	3.0	0.5	1.0	2.0
Estimated Space (ft.)	175	200	270	365	200	250	400
Slip Width (2 subs)	225	250	320	415	250	300	450
Slip Width (3 subs)	260	285	355	450	285	335	485

At each current speed, the average space required to make a good landing is estimated from the computer trajectories. To account for a reasonable number of poor landings, the space required is enlarged by an amount approximately equal to one standard deviation. Thus, the second row in Table I represents the space required to make most landings. Since provision must be made for at least two submarines in each slip, the third row provides for this accommodation by including the beam of another submarine and an additional modest space of about 15 feet for clearance. The fourth row shows the space required for nesting a third submarine by including an additional 35 feet. It is obvious that the estimates shown in Table I are the minimum necessary to accomplish the specified berthing; no "safety factor" is included.

Figures 16 - 21 show the results obtained for the SSBN type in a perpendicular berthing at 0.5, 1, and 2 kts. Since the SSBN type is larger, it develops more lateral momentum and is more difficult to control in currents than is the SSN type. Because of the difference in size, the SSBN type requires correspondingly more space to clear the pier than does the SSN type under the same experimental conditions. To estimate the slip width required to berth the SSBN type in perpendicular piers, consider Figures 18 and 19, for the 1-kt current. If the basic space required to berth one submarine is about 250 feet, then corresponding to the procedure used for the SSN type, two submarines would require 300 feet and three submarines (one nested) would take a slip width of 335 feet to accommodate them. Thus, if it were necessary to provide accommodation for both classes of submarines, the estimates for the SSBN type would be given primary consideration. The space requirements for SSBN submarines are also summarized in Table I.

When the pier is inclined to the axis of the channel, as it presently is, the component of the current on the beam of the submarine is reduced. If the current is ebbing, there is a component opposing the forward motion of the submarine; if the current is flooding, there is a component in the same direction as the forward motion of the submarine. Figures 22 - 25 show landings of the SSN-type submarine in both ebb and flood currents when the piers are oriented at 30° and 45°.

At an orientation of 30°, which is approximately the present pier orientation, the combination of rudder, tugs, and ship power produces the trajectory shown in Figure 22, for an ebb current of 1 kt. For a flood current of 1 kt, the trajectory shown in Figure 23 is achieved. The space required for berthing is on the order of 165 feet and is less than required in the corresponding perpendicular cases (Figures 9 and 11). These numbers apply only to the cases shown.

When the orientation is increased to 45°, the current on the beam is further diminished and the landings in both ebb and flood currents take still less space (Figures 24 and 25). However, the space saved (10 feet) probably does not warrant a change in orientation, if the conventional berthing arrangement is retained.

In the case of present berthing (about 30°), it was found that the basic space requirement for the SSN-type submarine is 180 feet. Therefore, about 230 feet is required to berth 2 submarines in a 1-kt current, and if nesting is considered, 265 feet will accommodate three submarines.

It has been pointed out that the current in the Thames channel is rarely expected to exceed 1 kt. It is therefore reasonable to consider waterfront design constrained by this condition rather than the infrequent larger current that is experienced during the spring thaw. Therefore, Table II was constructed to provide the basis for realistic consideration of redesign.

Table II. Estimated Slip Widths Required for Berthing Nuclear Submarines at Different Pier Orientations in a 1-Knot Current

	SSN			SSBN		
Pier Angle (degrees)	0	30	45	0	30	45
Estimated Space (ft.)	200	180	170	250	200	190
Slip Width (2 subs)	250	230	220	300	250	240
Slip Width (3 subs)	285	265	255	335	285	275

Tables I and II may be consulted to determine the effect of varying current and/or pier angle in the space required for the two submarine classes considered.

The computer experiments relating to the sawtooth concept were designed to test the hypothesis that the submarine could be adequately controlled to achieve successful landing in flood and ebb currents by applying rudder, ship power, and tug power. Figures 26 and 27 show two such cases where a 1-kt head current prescribes an initial forward speed of 4 kts for the SSN-type nuclear submarine.

In Figure 26, an initial setting of 30° right rudder induces deviation of course after 200 feet of travel. As the submarine approaches the berth, 1/3 reverse tug power is applied fore and aft, with the tugs at 45° as shown in the insert. This combination of tugs and rudder is sufficient to ease the SSN into the proper berthing orientation and to reduce the forward speed to zero (in conjunction with the opposing current). The arrows show successive positions of the submarine as it is berthed adjacent to another submarine.

Figure 27 shows another landing of the SSN type under the same conditions. In this case, the rudder is again at right 30°, but at the point denoted by *, ship backing power of 1/3 is applied to reduce speed, and 1/3 back tug power (bow tug only) is applied as shown. The result is a landing similar to that shown in Figure 26. The combination of rudder, ship power, and tugs appears to make landing relatively uncomplicated in a 1-kt current initially on or near the bow. For currents of smaller magnitude, submarine control is found to be even easier to achieve, as might be expected.

For greater head currents, it becomes difficult to hold the submarine, once the current is permitted to develop an appreciable component on the beam and, in this case, the landing can be dangerous. This is shown in

Figure 28, where the ship speed of 5 kts and a 30° right rudder are the initial conditions in a 2-kt head current. Soon after the submarine deviates from the current heading, the bow tug at 1/3 back is employed to restore heading, at point A. Failing to do so, the bow-tug power is increased to 2/3 back at B. The submarine lateral motion is already unstable and it becomes impossible to overcome the lateral momentum. The submarine continues to rotate and to move laterally with little loss of momentum.

It became apparent, during computer experimentation, that the key to docking successfully, in head currents, was to keep the bow headed into the current as much as possible. This is not difficult to accomplish in currents up to 1 kt, but at 2 kts it can be troublesome, as shown in Figure 28, even though some successful dockings were achieved at 2 kts. It should be borne in mind that for the purposes of this experiment, it was assumed that the 2-kt current exists over all space. If there is any sheltering in the vicinity of the piers, control is improved considerably.

In a following current of 1 kt, the forward ship speed of 2 kts prescribes a much larger travel distance to effect control. Figure 29 shows such a docking of the SSN type at a sawtooth pier. Initially, 30° right rudder is commanded, and the bow and stern tugs apply 2/3 power in opposite directions to assist the clockwise rotation which is now desirable. From A to B, the rudder is restored to O and the bow and stern-tug power is reduced to 1/3. At B, the submarine applies 1/3 back power to achieve zero speed at point C, the landing site.

Although the rudder is not very effective in following currents, the tendency is for the current to create stability and resist deviation of submarine heading. Consequently, control is not overly difficult to achieve in following currents.

In general, it may be said that the experiments described here suggest that sawtooth berthing of nuclear submarines can be achieved in the environment of the Thames channel, under expected current conditions, with the techniques presently used. The tendency to resist deviation from initial orientation makes this mode of landing potentially easier than the head-current case. In any event, landing at or below 1 kt is not expected to create handling difficulties regardless of current direction. Landings in head currents above 2-kts could be dangerous. However, such conditions are not expected to occur at times other than that of the annual spring thaw.

All of the foregoing discussion on berthing of SSN-type submarines in the sawtooth configuration were found to apply in the case of the SSBN-type submarine. Consequently, corresponding examples were not included.

CONCLUSIONS

This study is comprised of many facets each of which has contributed something to the overall understanding of the problem and to its solution. The following conclusions have been distilled from all of the information gleaned from: literature surveys, data collection, personal interviews, and computer experiments.

1. Of all the environmental factors that inhibit landing of nuclear submarines, current is believed to be by far the most dominant. Although the current rarely exceeds 1 kt, even a small current on the beam makes present landing difficult.
2. The results for the 0.5-kt current case show space requirements not unlike those required in present landing operations. This reinforces the suggestion that even during "slack water" periods currents are present that hamper landing operations.
3. If nuclear submarine landings had to be made in all current conditions, it is doubtful that the present berthing arrangement, with limited slip width, would be satisfactory.
4. Regardless of the berthing arrangement, tug

attendance is mandatory, so long as any trace of current exists.

5. As the angle of the pier is deviated from a position perpendicular to the current, control of the submarine improves. Optimum pier orientation is achieved, when the submarine can align itself most nearly parallel to the current, upon ingress.

6. The sawtooth berthing concept provides the easiest submarine handling situation at and below 1.5-kts head current and up to 2-kts following current. This accounts for almost all current conditions.

7. Ease of handling achieved in sawtooth berthing will permit nesting of 2 submarines in each berth.

8. If the present berthing arrangement is retained, a simple expedient to accommodate nuclear submarines could be achieved by removing every other pier. This would provide space to berth a third submarine in each slip, but landing in a 1-kt current that causes the submarine to bear down on one already docked will probably increase the incidence of ulcers among skippers.

9. The optimum slip width, in the present berthing orientation, is about 230 feet for SSN-type

submarines and about 250 feet for SSBN-type submarines (without multiple berthing).

RECOMMENDATIONS

Based upon the results and conclusions of this study, and upon the practical aspects of this particular situation, the following recommendations are made:

1. The present orientation may be retained, if the slip width is increased to 230 feet, to berth two submarines of the SSN type. The piers should be lengthened to accommodate the longest nuclear submarine expected and the aft ends of the piers should be indented to house stern planes. Also, the pier ends should be buffered to minimize possible collision damage.
2. The optimum slip width given above applies to berthing of 2 submarines in each slip. Multiple berthing is not recommended in this pier orientation.
3. If the present orientation is retained and if the recommended slip width is adopted, the berthing arrangement would be suitable for landings in currents up to 1 kt. If higher currents are

present, landing in this orientation is not recommended.

4. It is recommended that the sawtooth berthing arrangement be adopted in the space now occupied by piers 1 - 9. The sawtooth provides easier ingress in head currents up to about 1.5 kts and in following currents up to about 2 kts. If 2 submarines are nested in each berth, then the requirements for housing nuclear submarines are met [4].

5. If the sawtooth concept is adopted as recommended, then the rest of the piers may be used to accommodate conventional submarines. If that is the case, no change in slip width or pier length is required. However, it seems reasonable that perhaps one wide slip, as recommended in 1. above should also be included with the sawtooth arrangement.

ACKNOWLEDGMENTS

In order to carry out the study reported here, it was necessary to enlist the aid of many people in different places. Without such cooperation, it would have been virtually impossible to accumulate the information necessary to fully understand the problem and to arrive at a reasonable solution.

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OCEANICS staff members were particularly helpful. Theodore Sargent programmed the dynamic equations of the submarines and executed many successful landings, on the OCEANICS digital computer. Bert Kieffer drew all the figures and he and August Lehman participated in discussions to conceive radical berthing designs. Lois Savastano typed the manuscript.

The authors appreciate the assistance of all those who contributed to this study and, in particular, of those whose names were inadvertently omitted.

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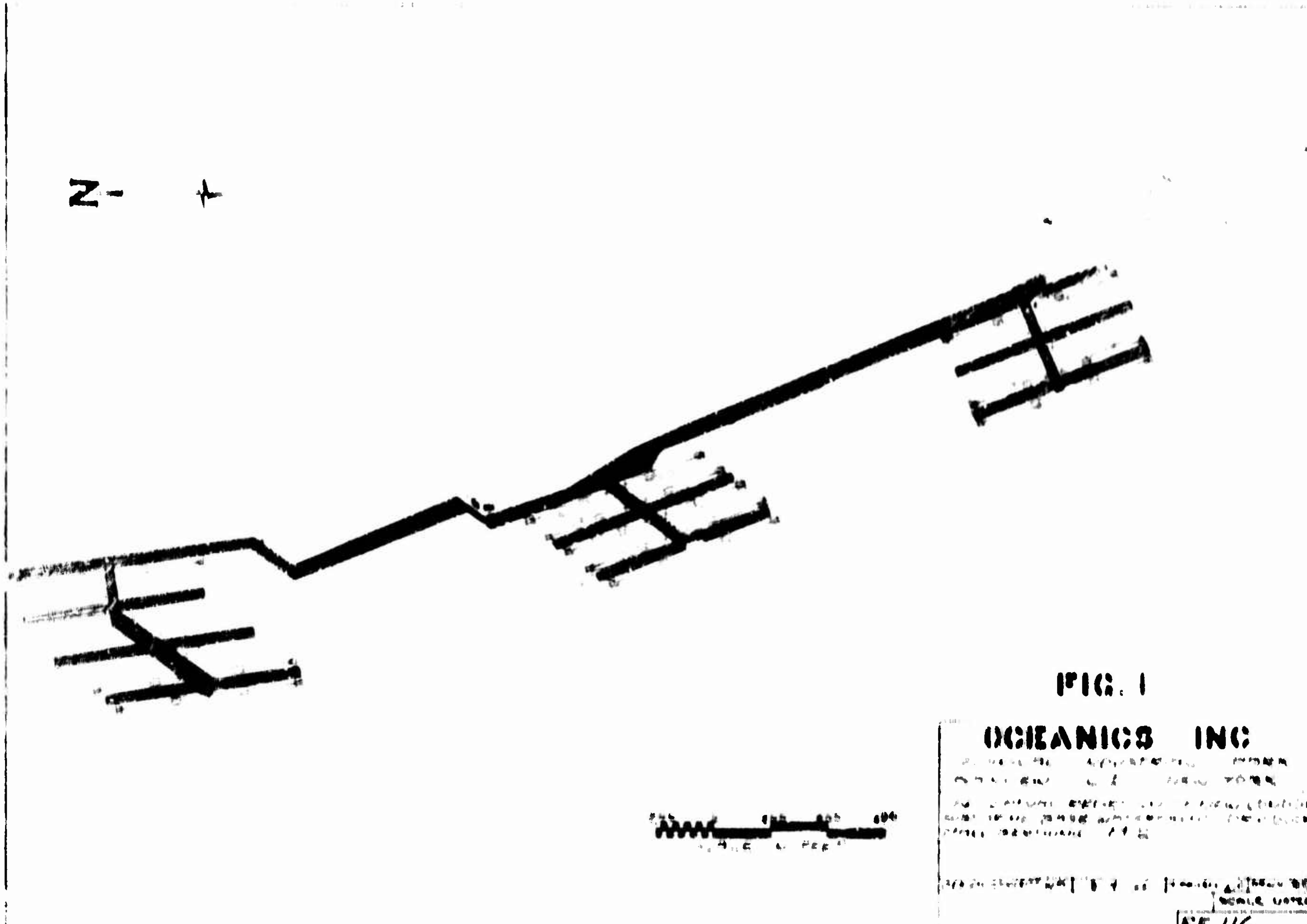

FIG. 1

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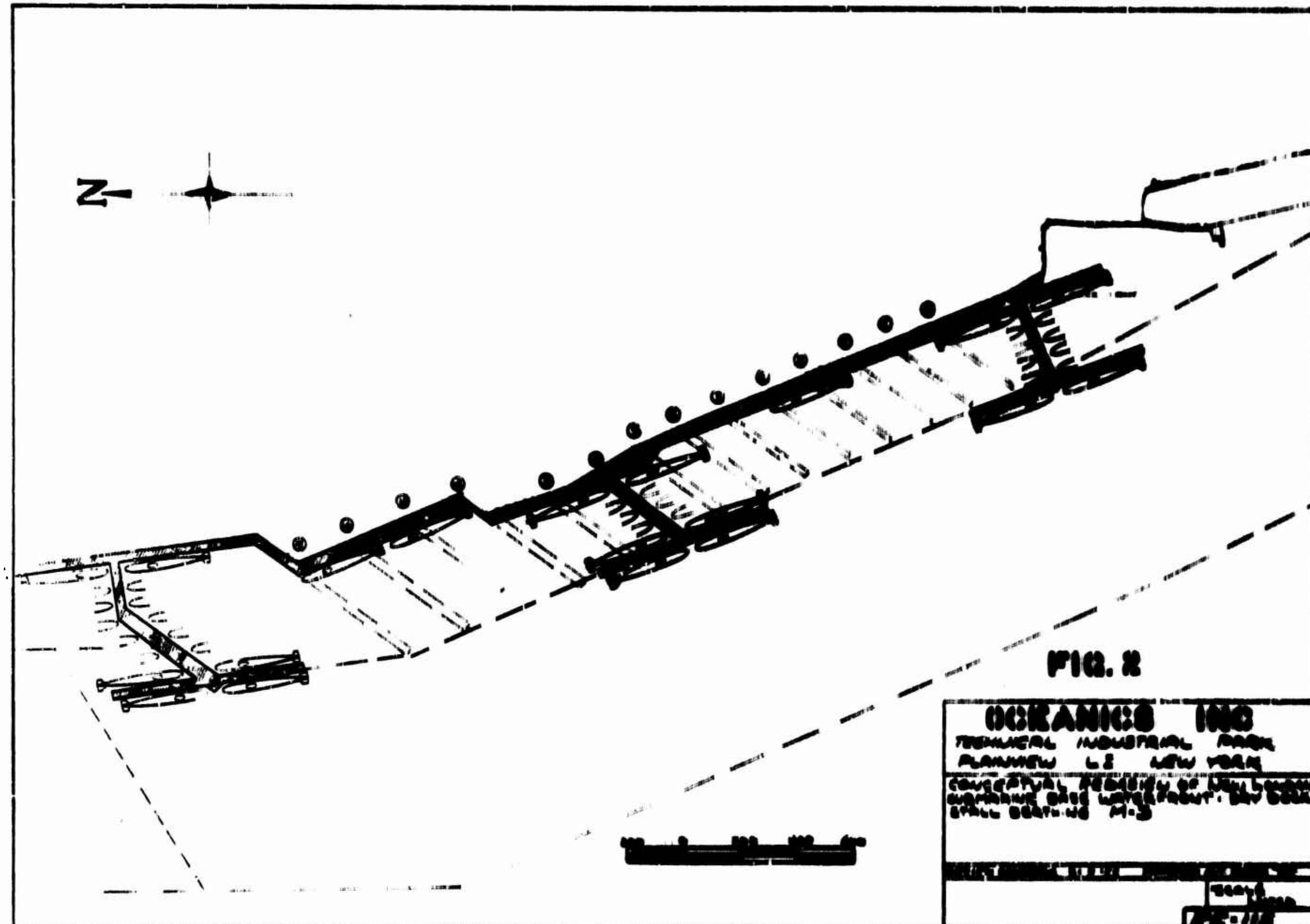
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FIG. 2

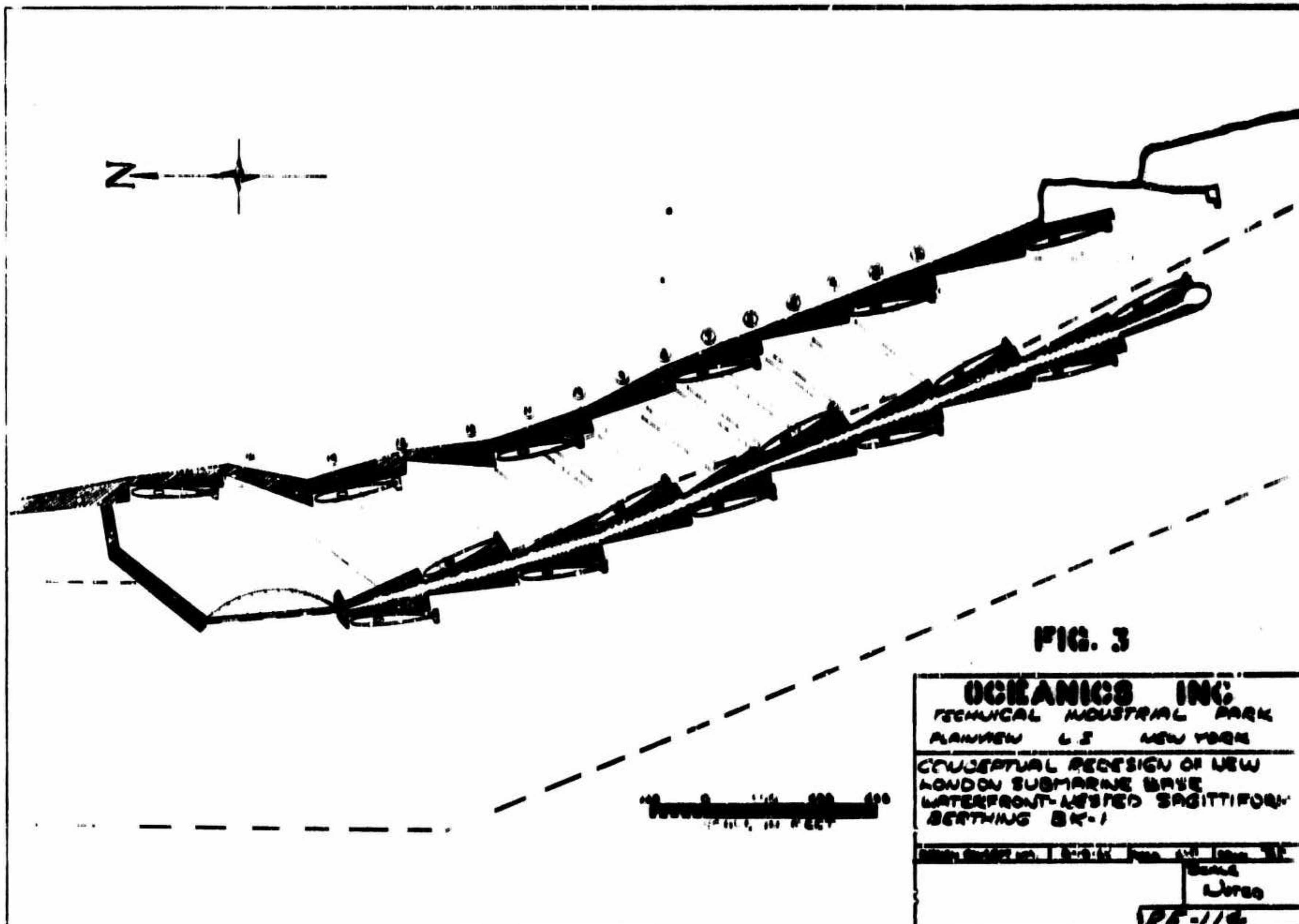
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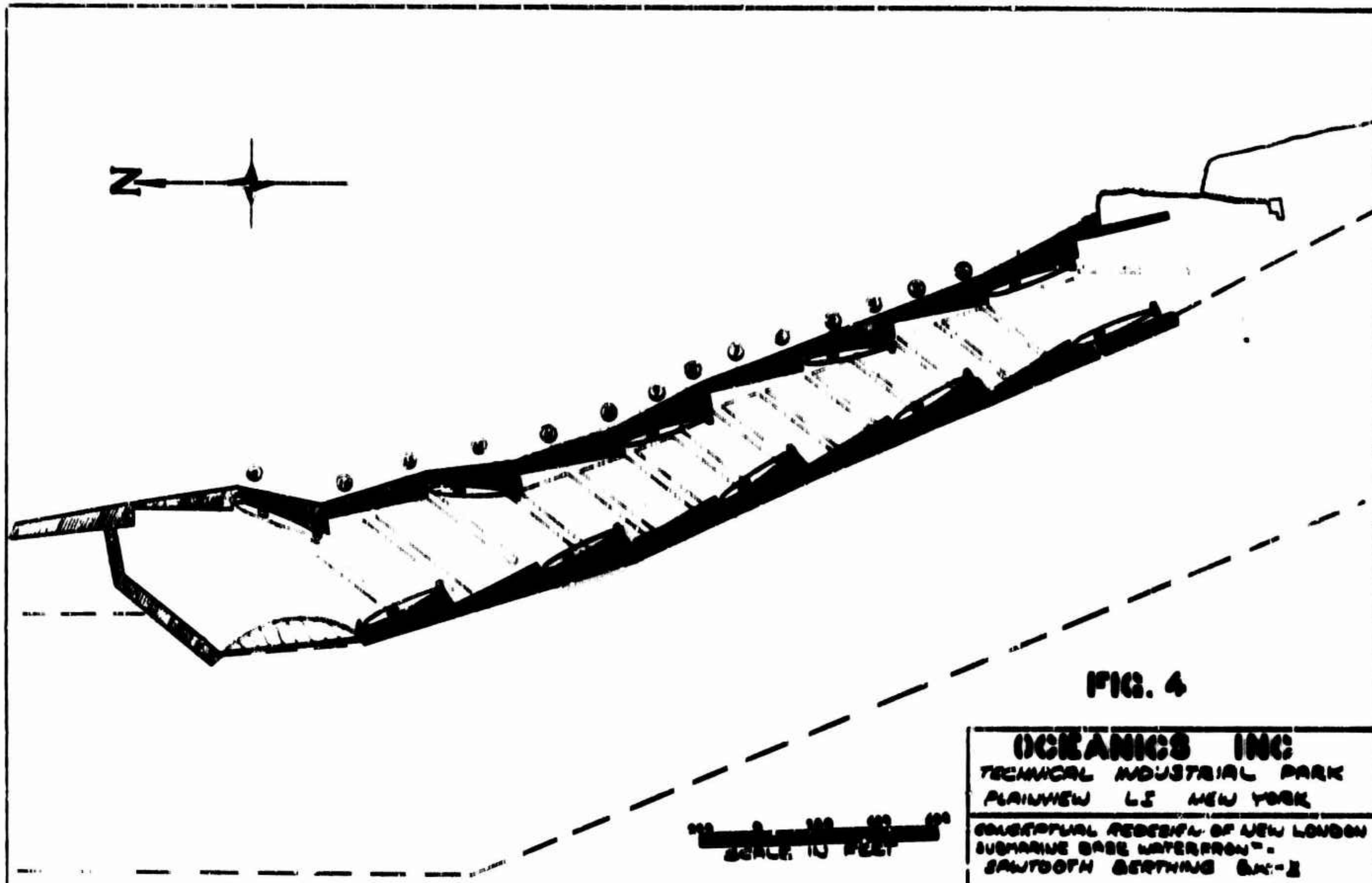
FIG. 3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SCALE IN FEET
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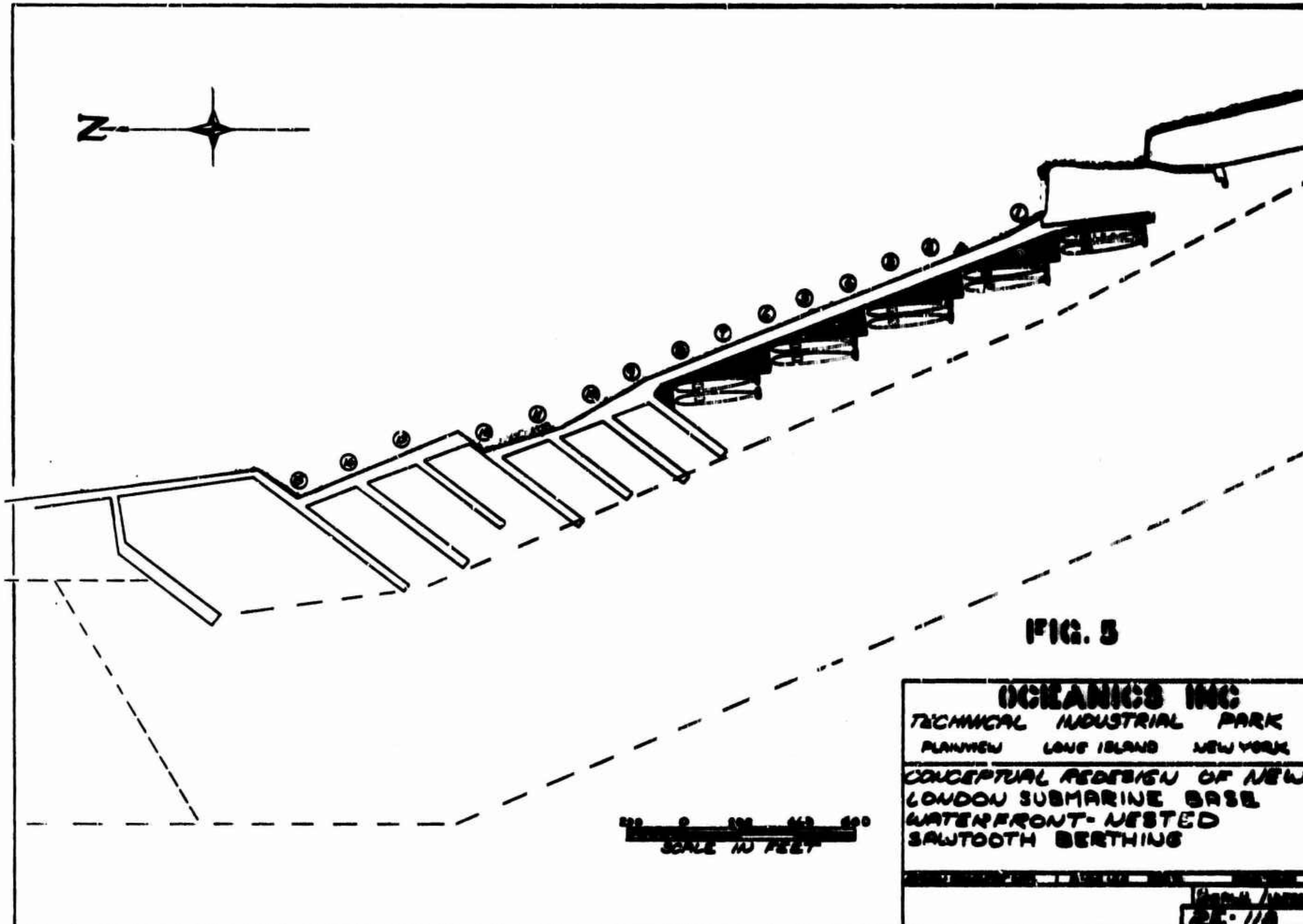
CONCEPTUAL REDESIGN OF NEW LONDON SUBMARINE BASE WATERFRONT - SAWTOOTH BERTHING

FIG. 4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CONCEPTUAL REDESIGN OF NEW LONDON SUBMARINE BASE WATERFRONT- NESTED SAWTOOTH BERTHING
SCALE IN FEET

FIG. 5

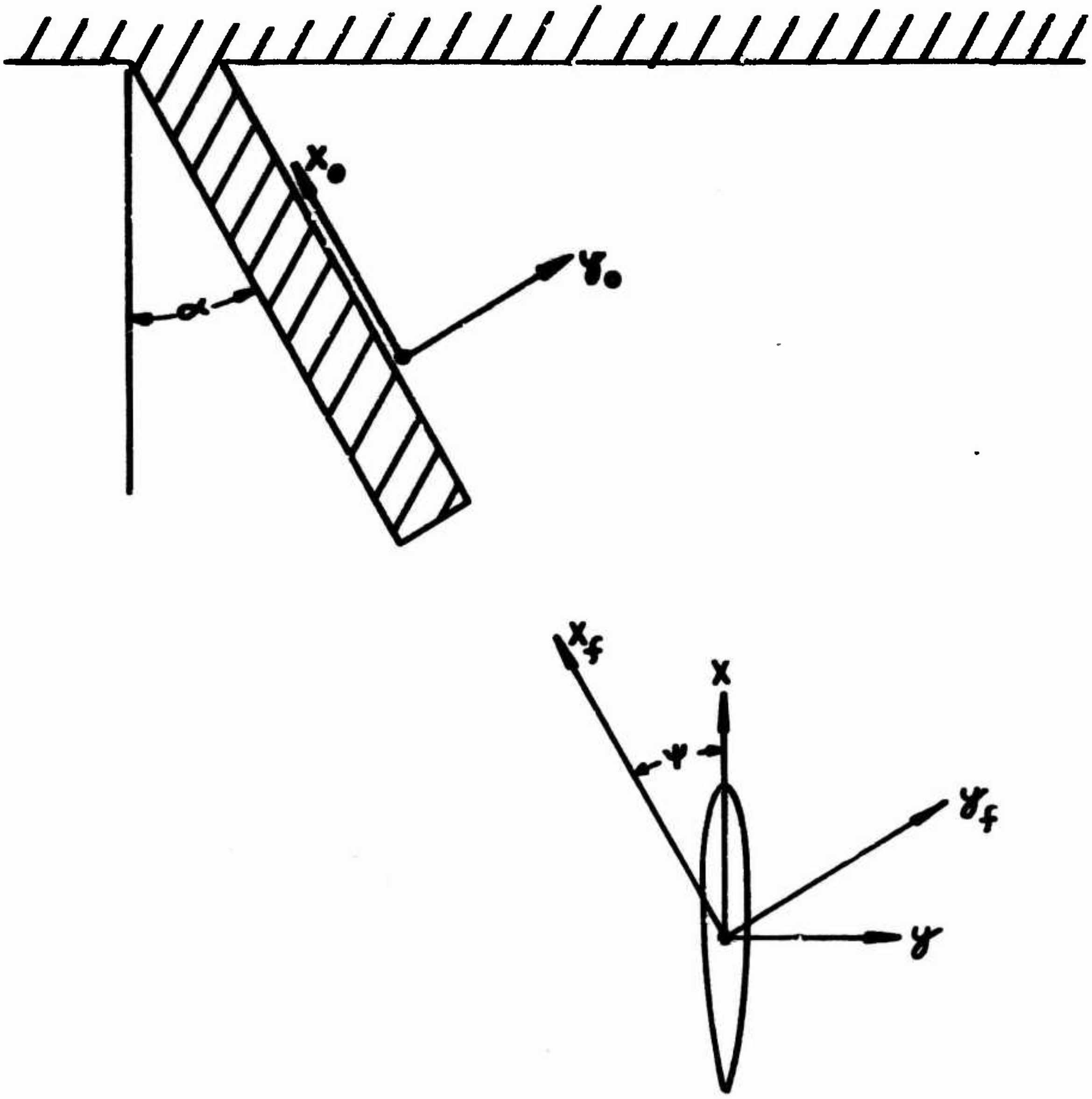

Figure 6 Reference frames on submarine (x,y); drifting fluid inertial frame (x_f, y_f); and fixed inertial reference frame (x_0,y_0), illustrating geometric arrangements.

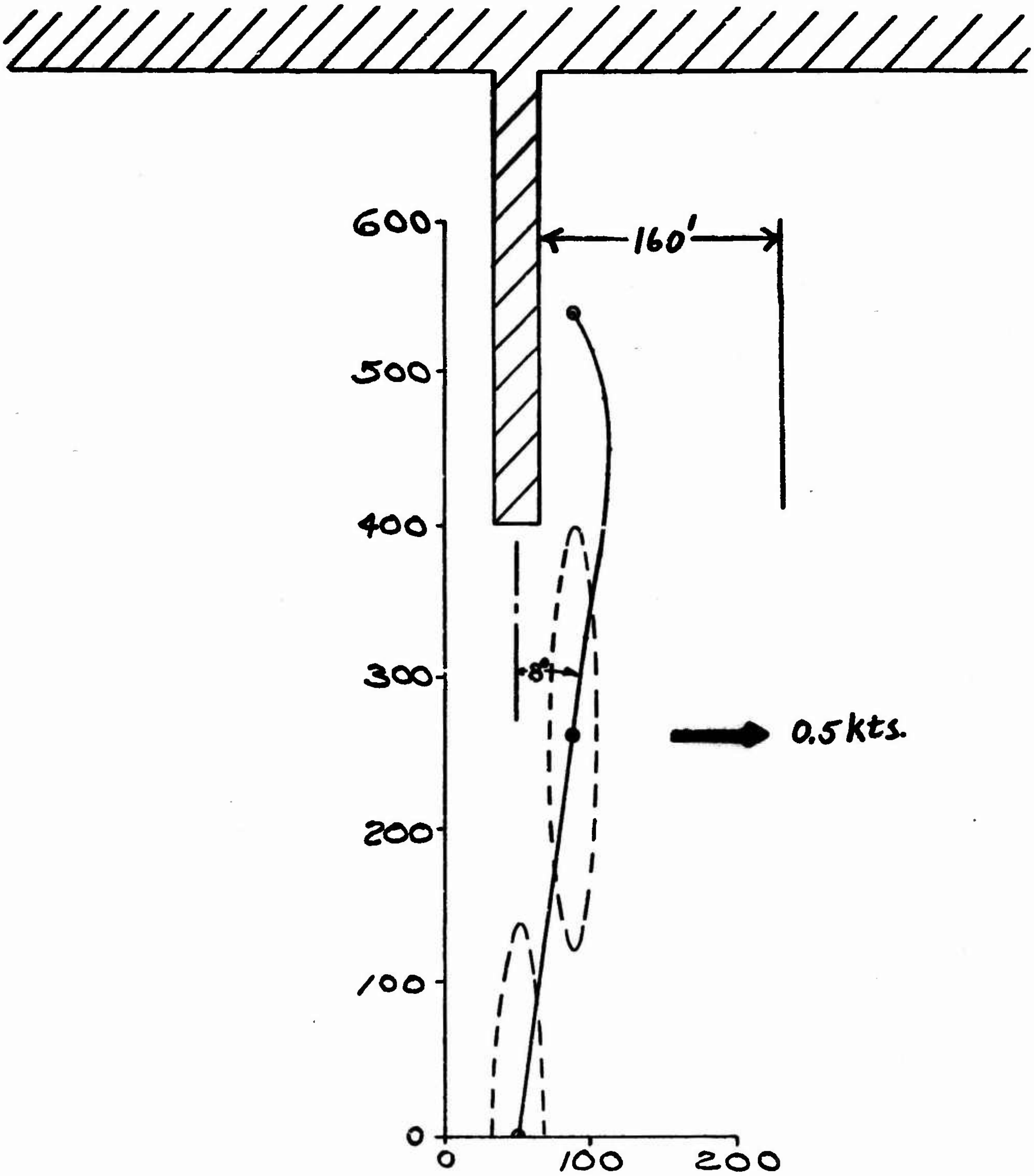

Figure 7. SSN type; port landing in 0.5-kt current at perpendicular pier.

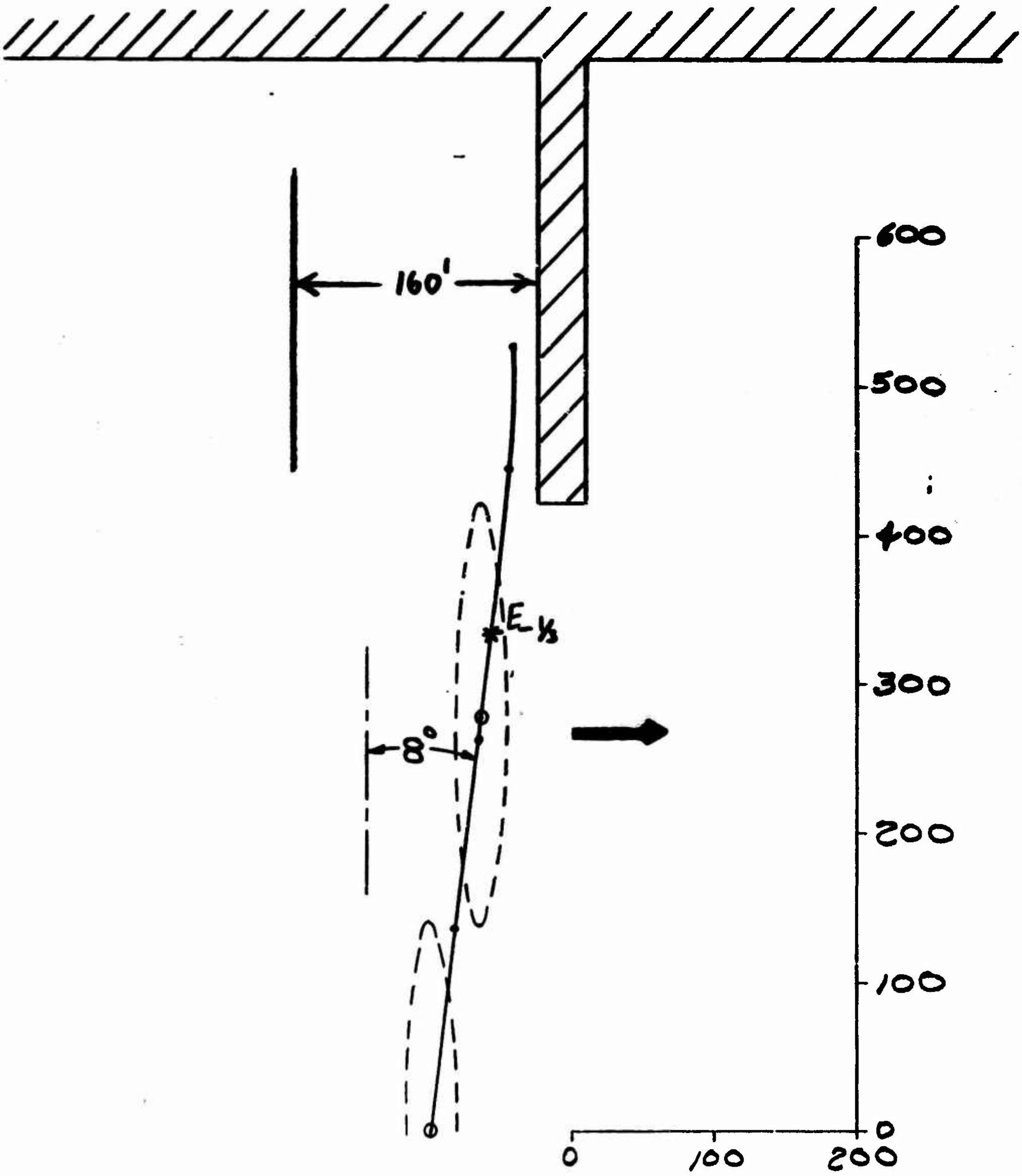

Figure 8. SSN type; starboard landing in 0.5-kt current at perpendicular pier.

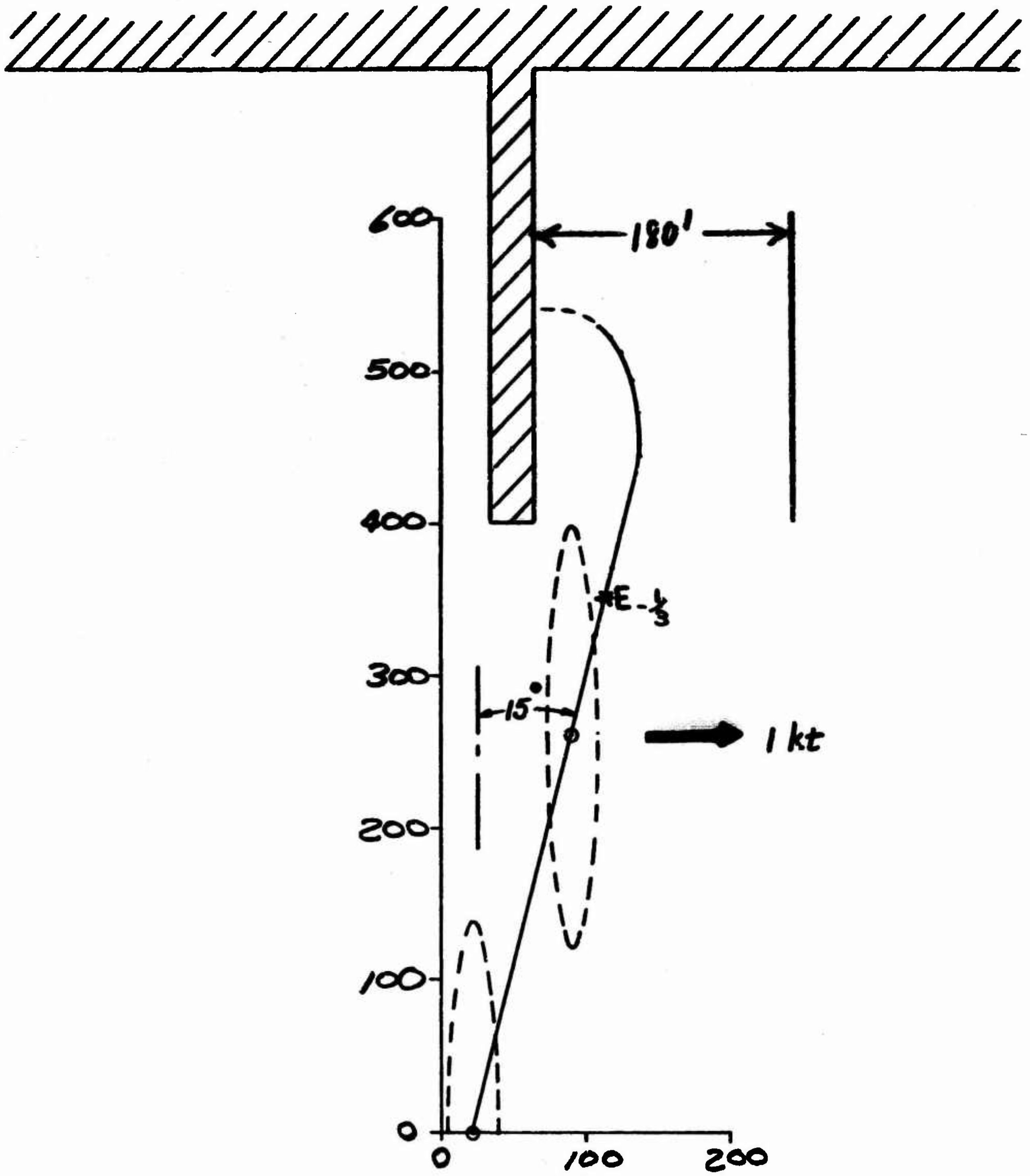

Figure 9. SSN type: port landing in 1-kt current at perpendicular pier.

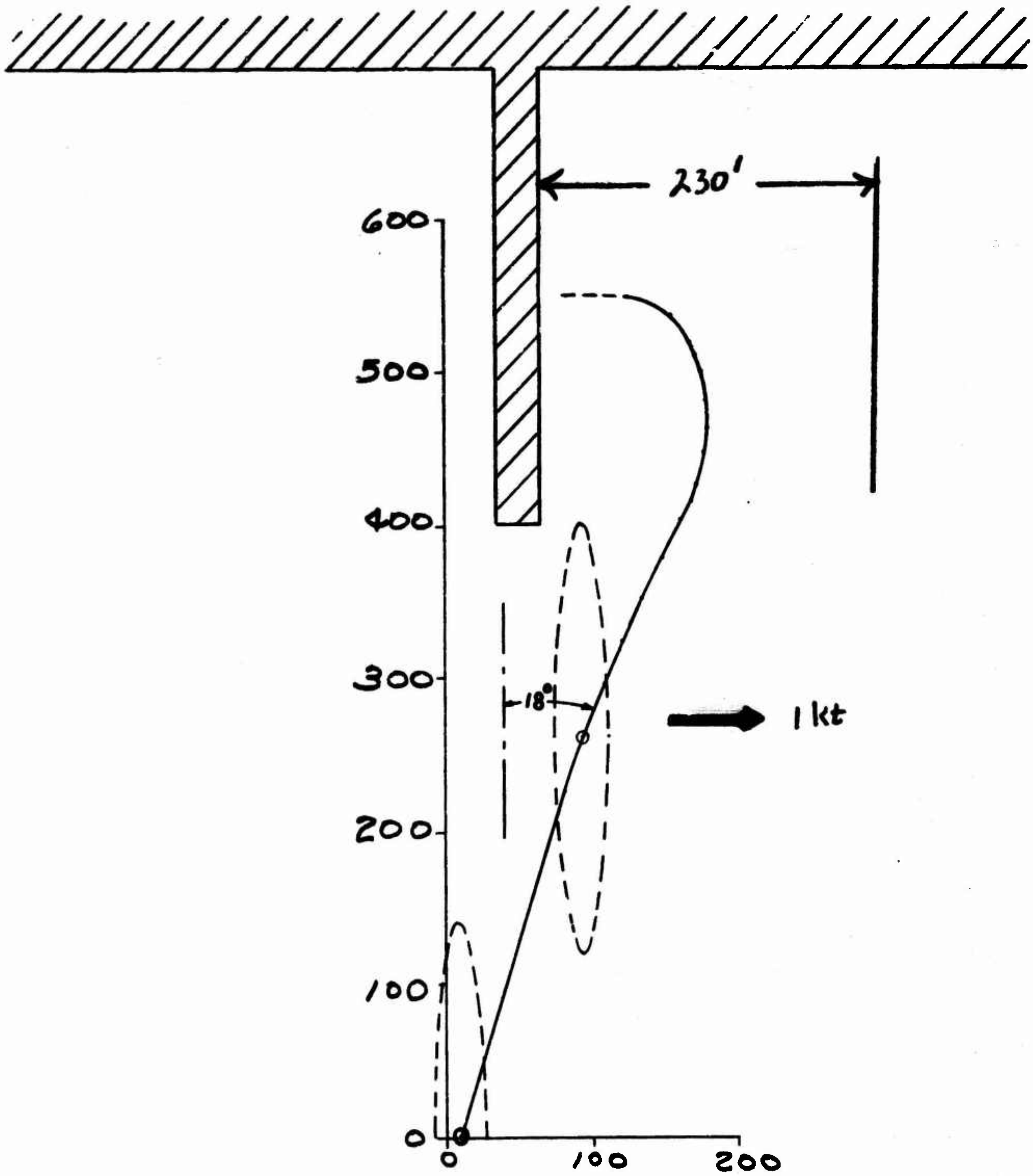

Figure 10. SSN type; port landing in 1-kt current at perpendicular pier. Submarine power not utilized.

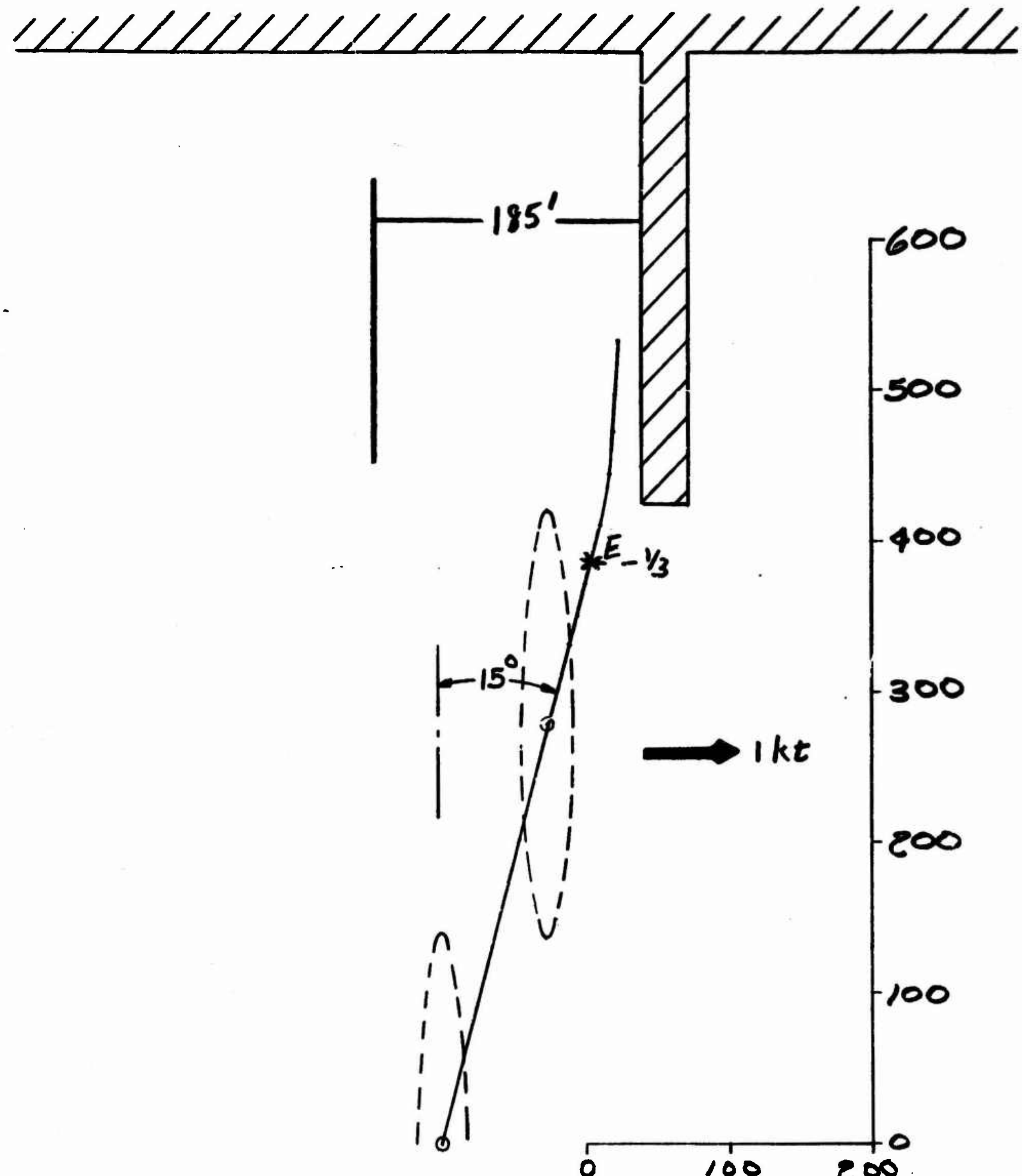

Figure 11. SSN type; starboard landing in 1-kt current at perpendicular pier.

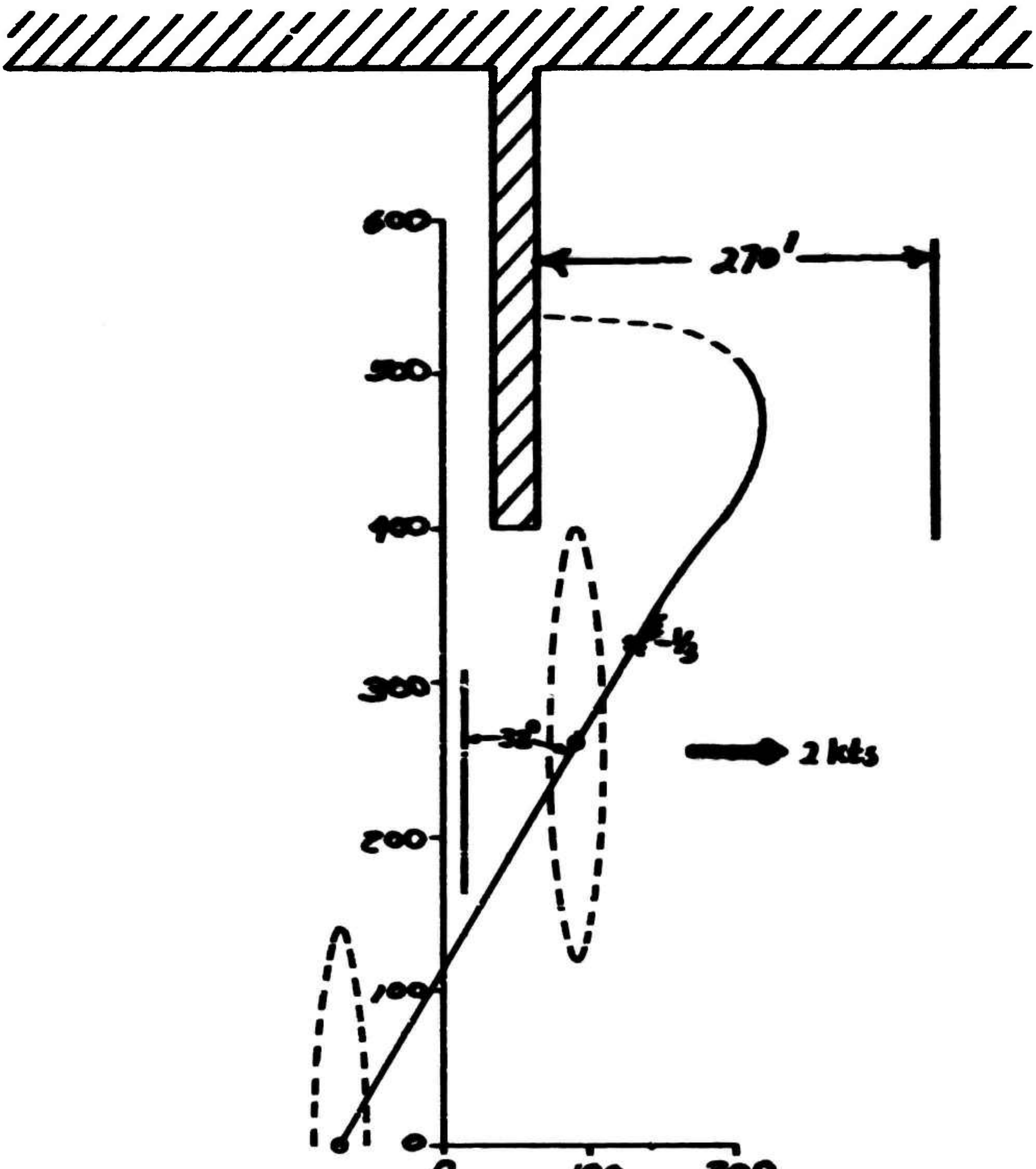

Figure 12. SSN type; port landing in 2-kt current at perpendicular pier.

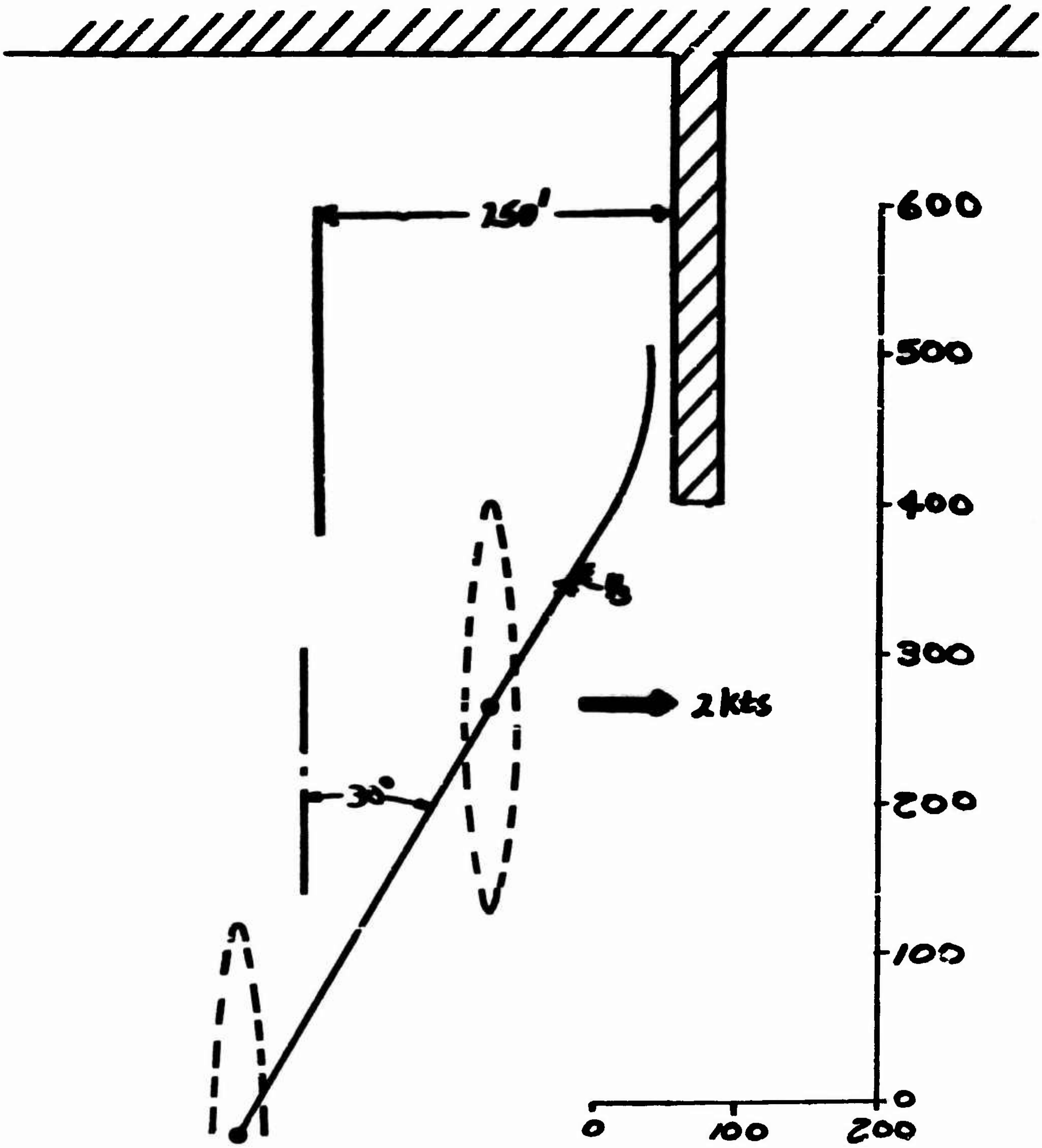

Figure 13. SSN type; starboard landing in 2-kt current at perpendicular pier.

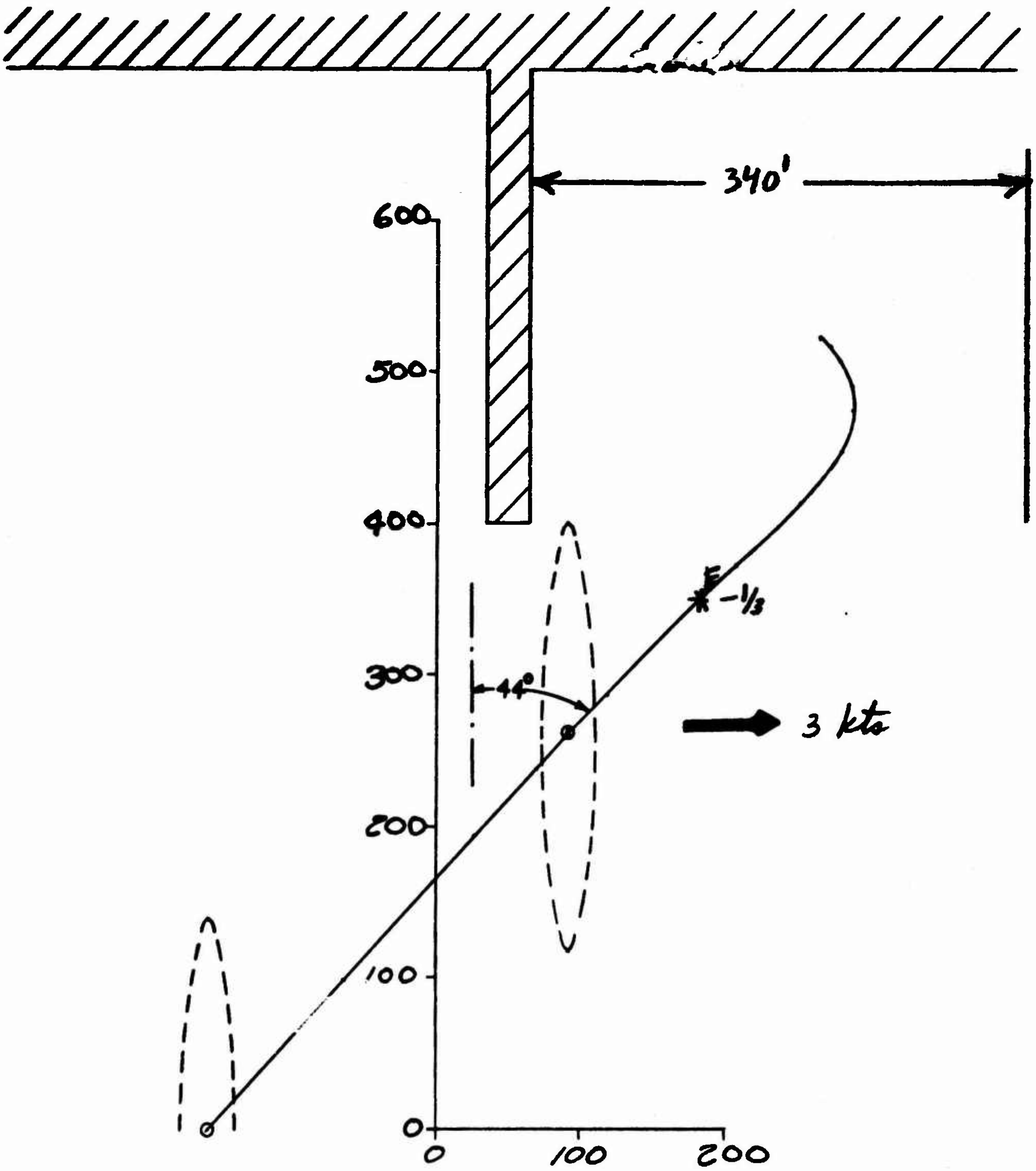

Figure 14. SSN type; port landing in 3-kt current at perpendicular pier.

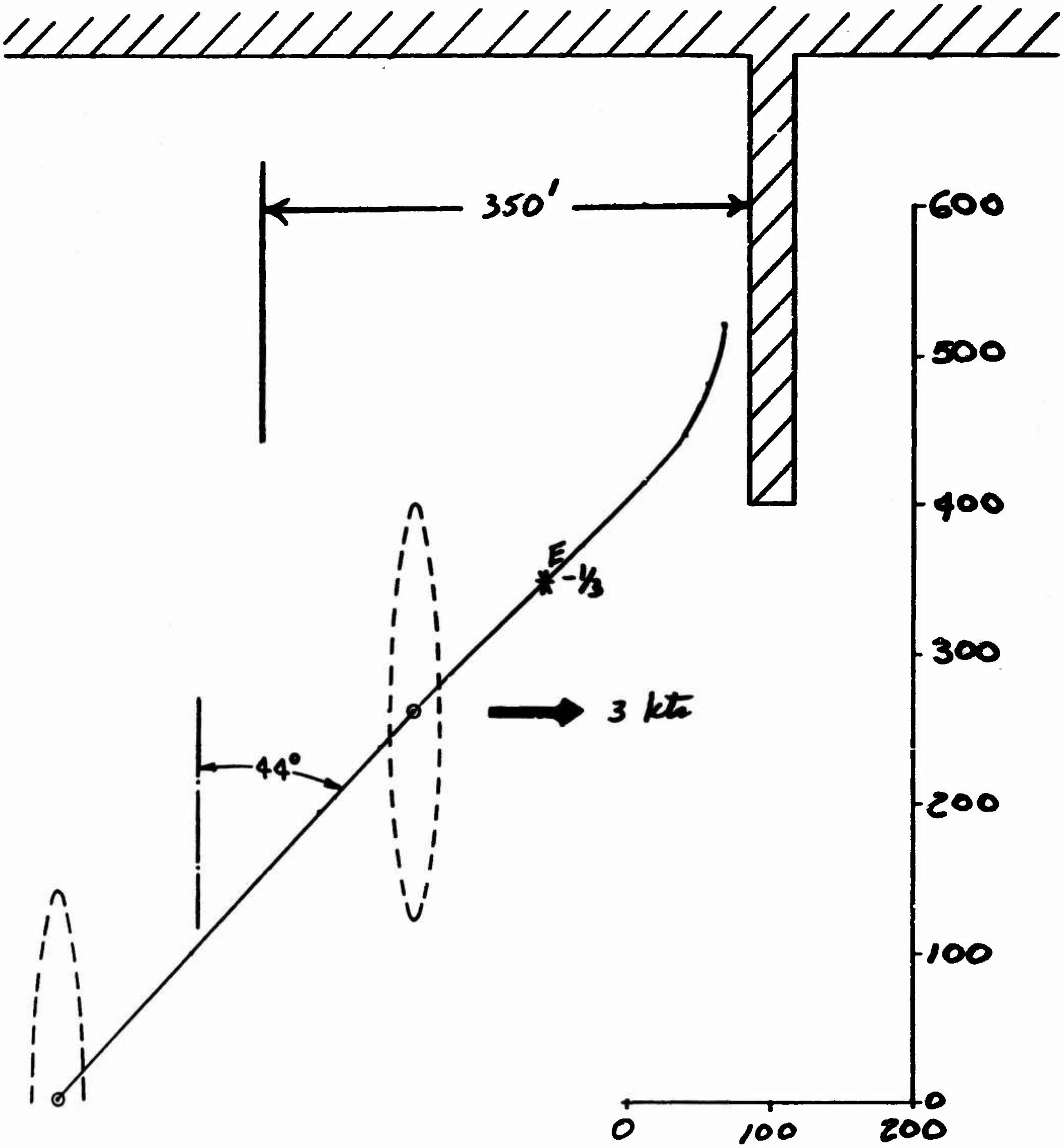

Figure 15. SSN type; starboard landing in 3-kt current at perpendicular pier.

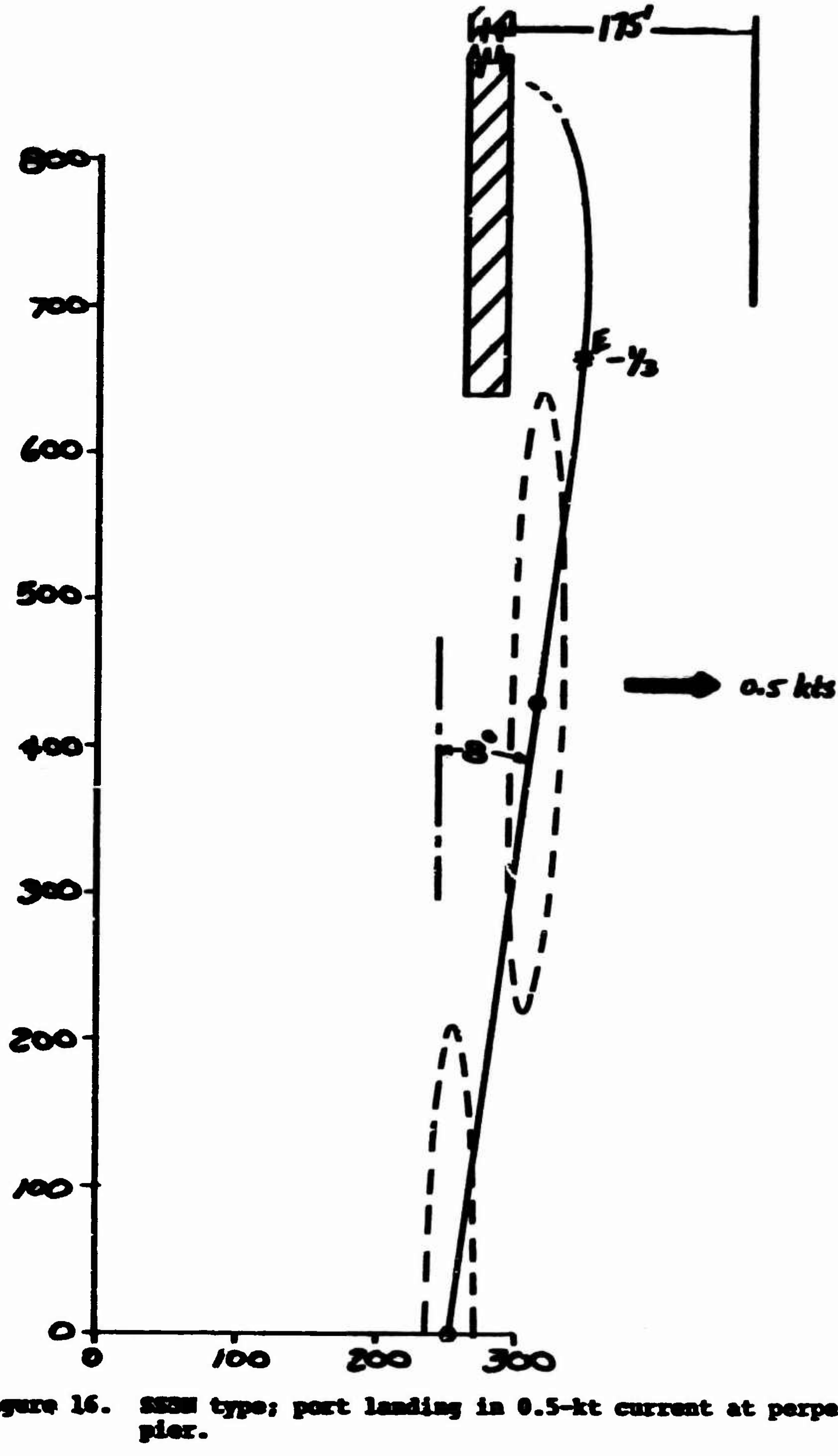

Figure 16. SSBN type; port landing in 0.5-kt current at perpendicular pier.

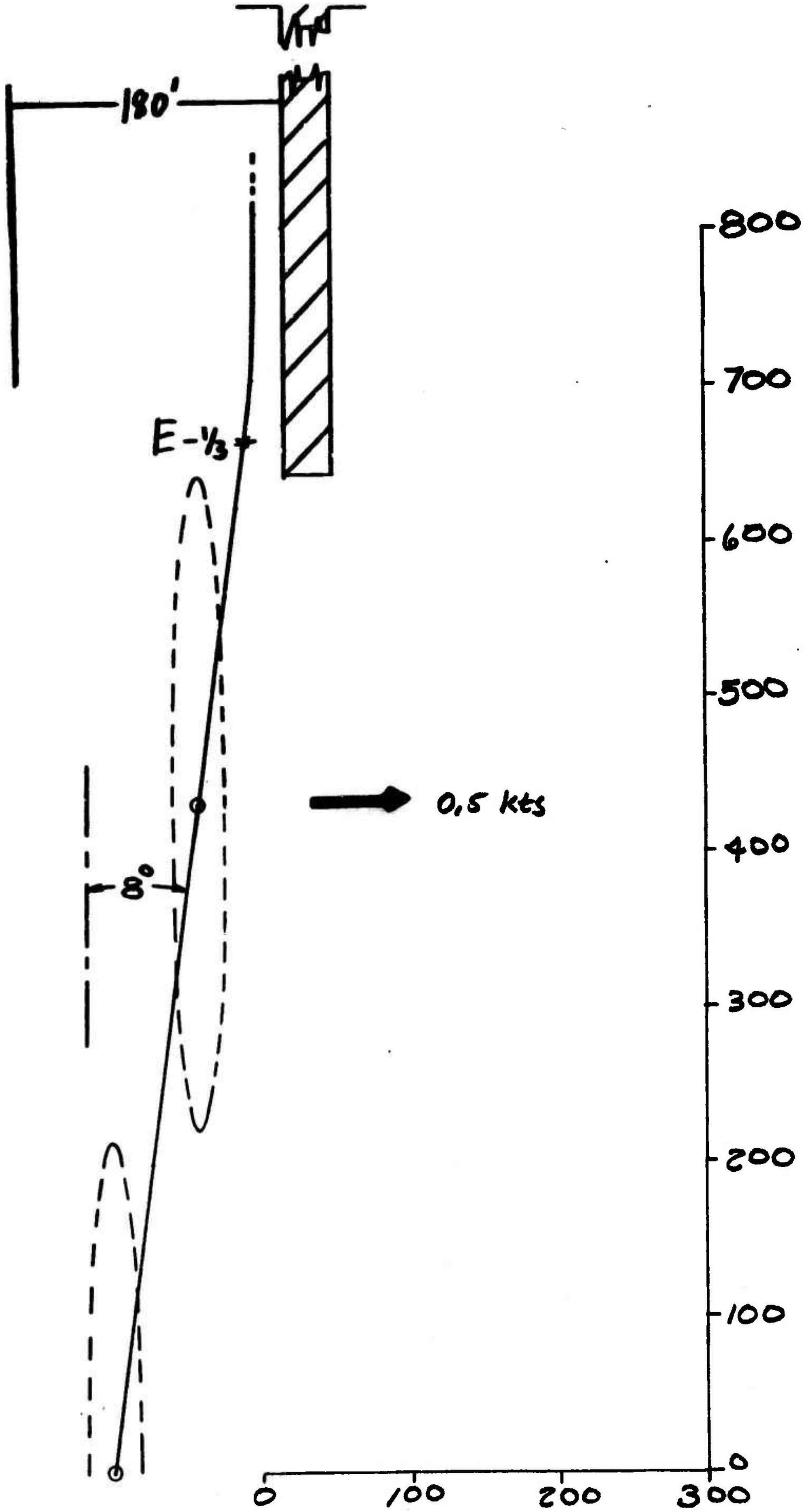

Figure 17. SSBN type; starboard landing in 0.5-kt current at perpendicular pier.

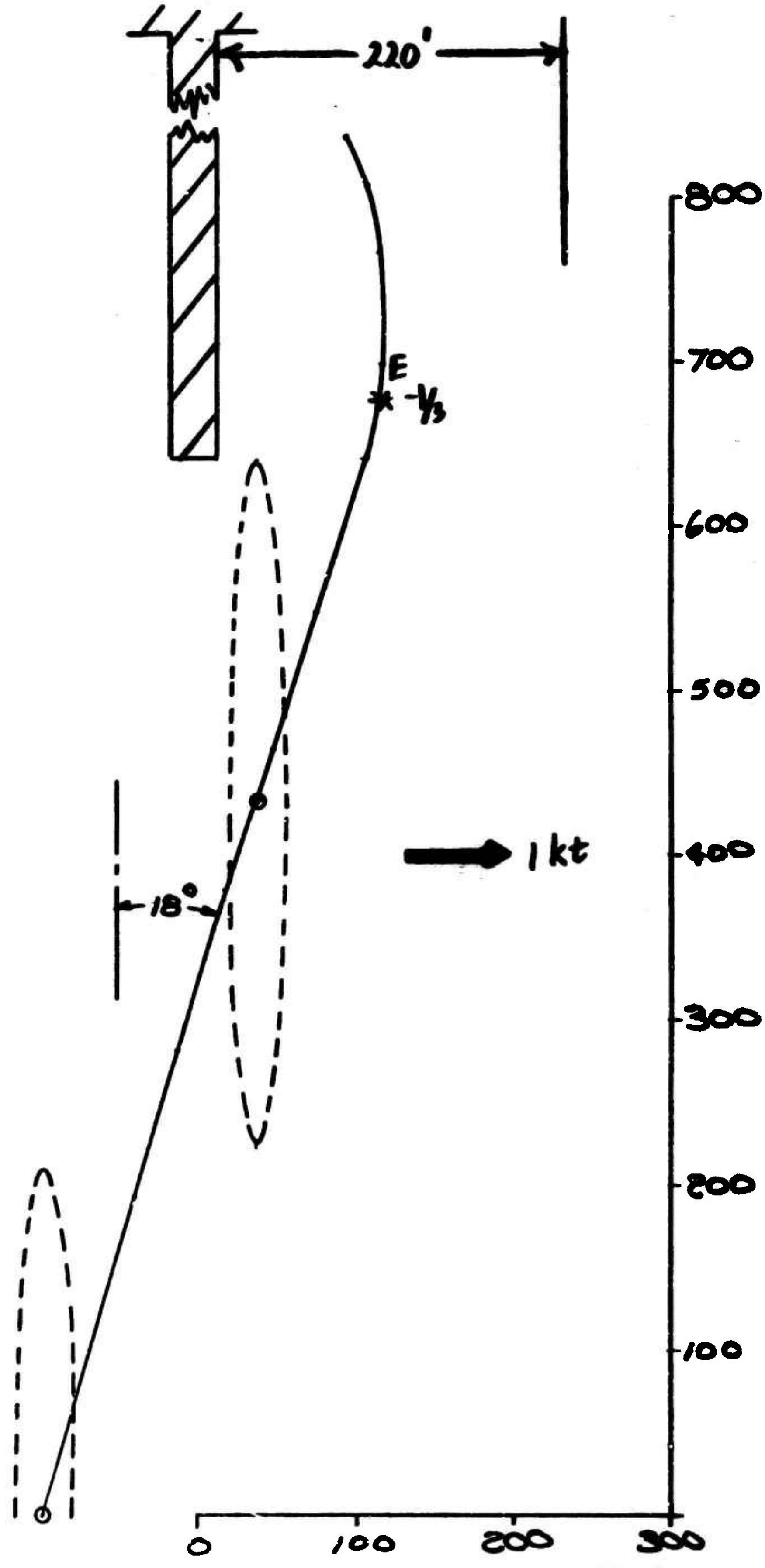

Figure 18. SSBN type; port landing in 1-kt current at perpendicular pier.

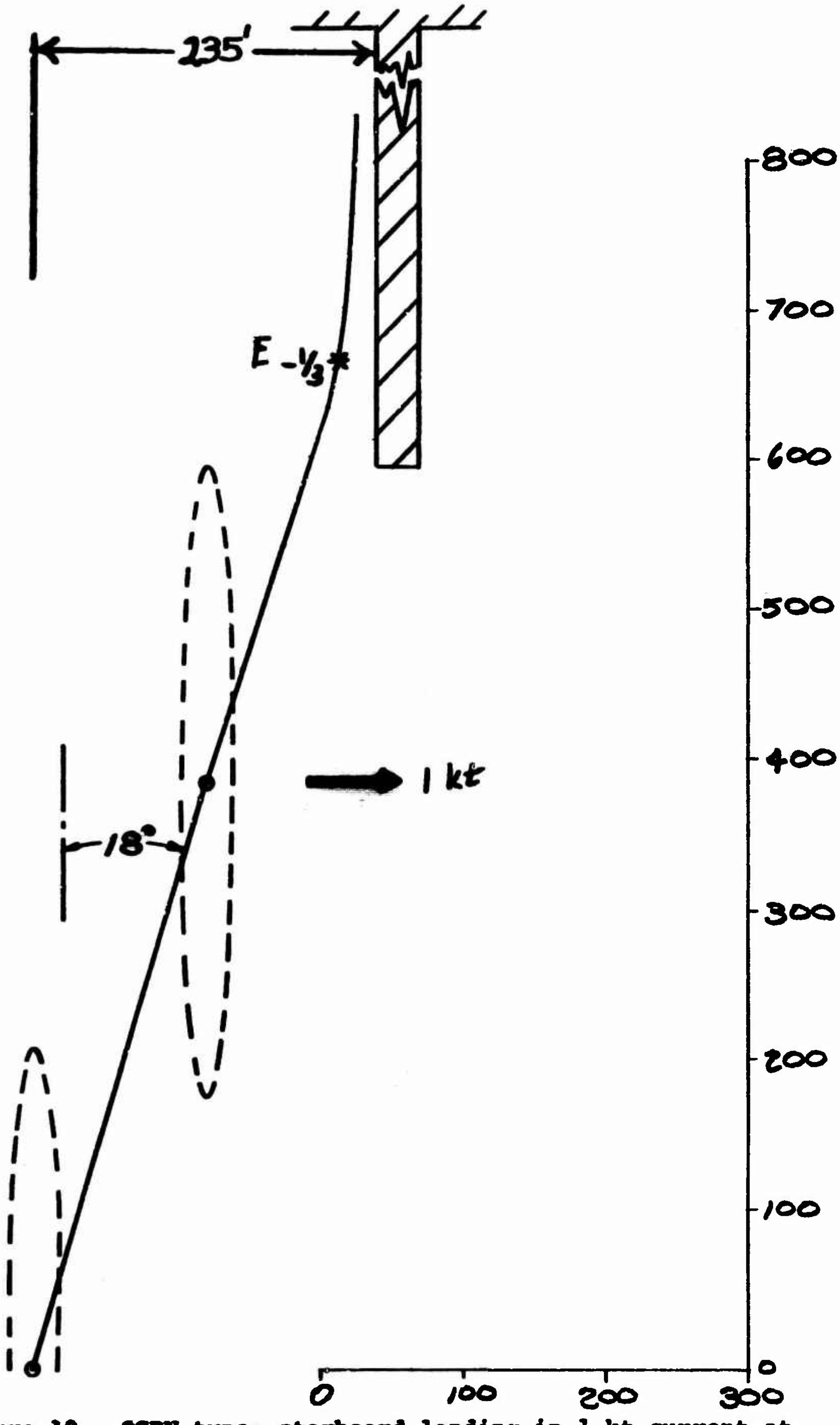

Figure 19. SSBN type; starboard landing in 1-kt current at perpendicular pier.

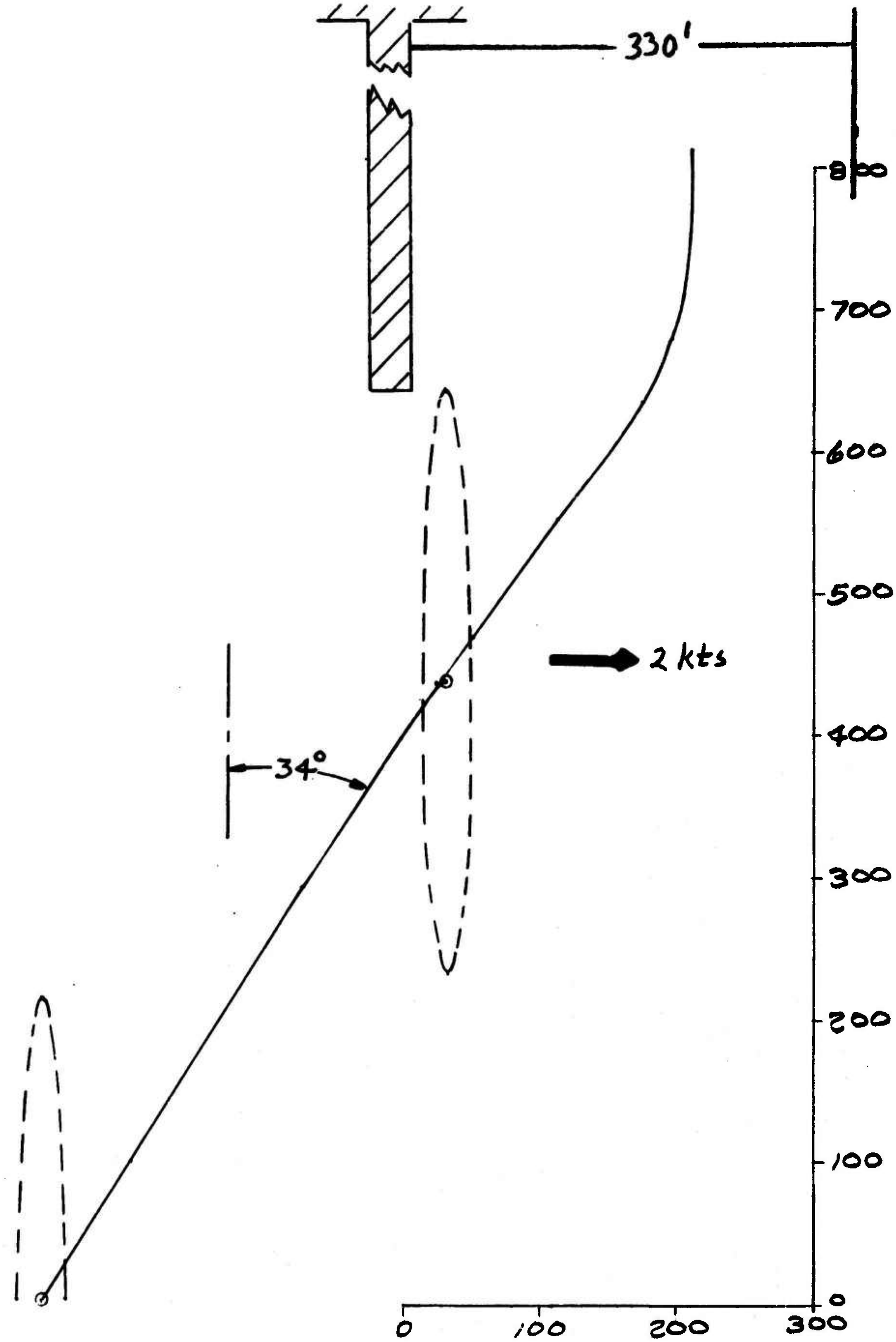

Figure 20. SSBN type; port landing in 2-kt current at perpendicular pier.

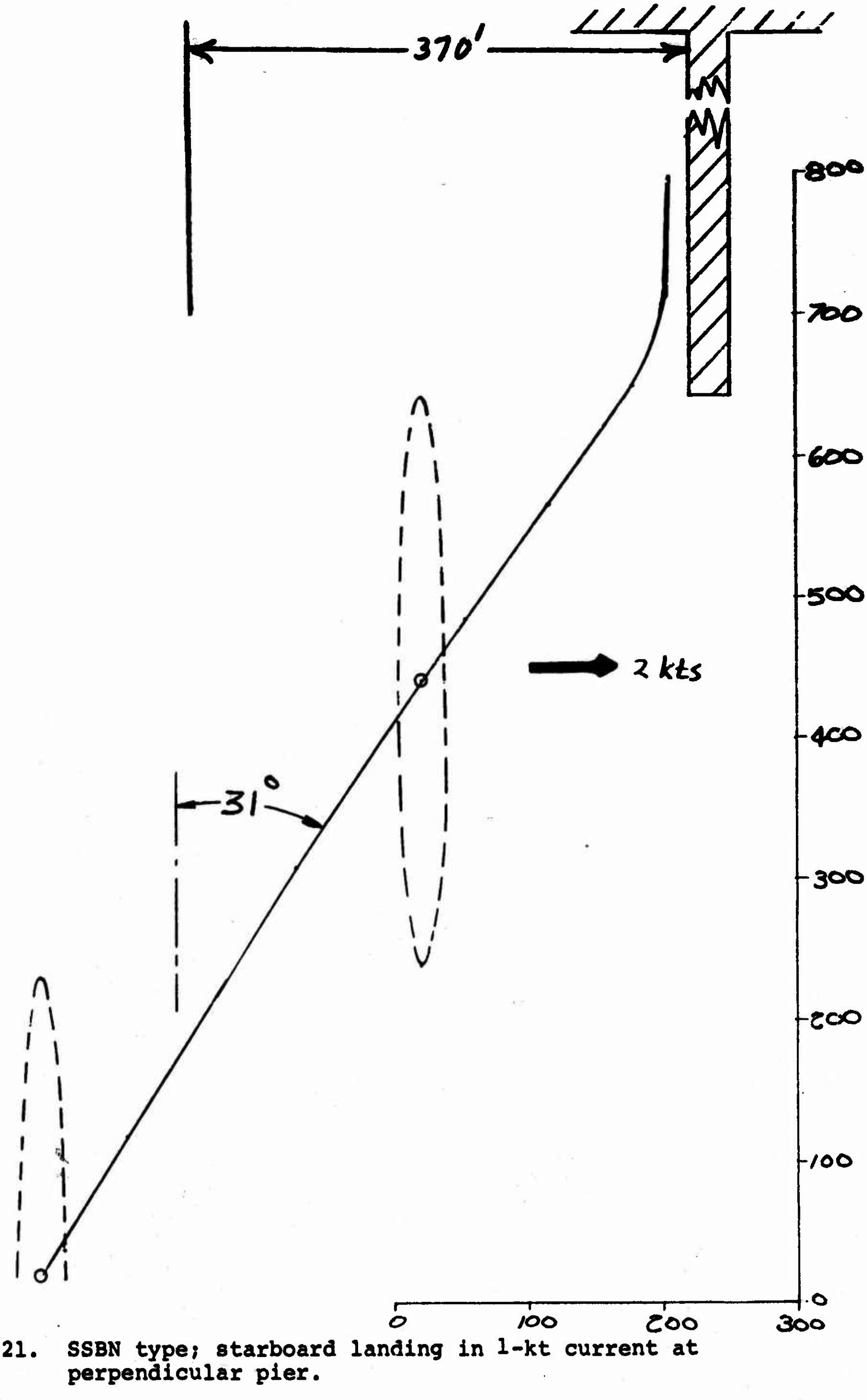

Figure 21. SSBN type; starboard landing in 1-kt current at perpendicular pier.

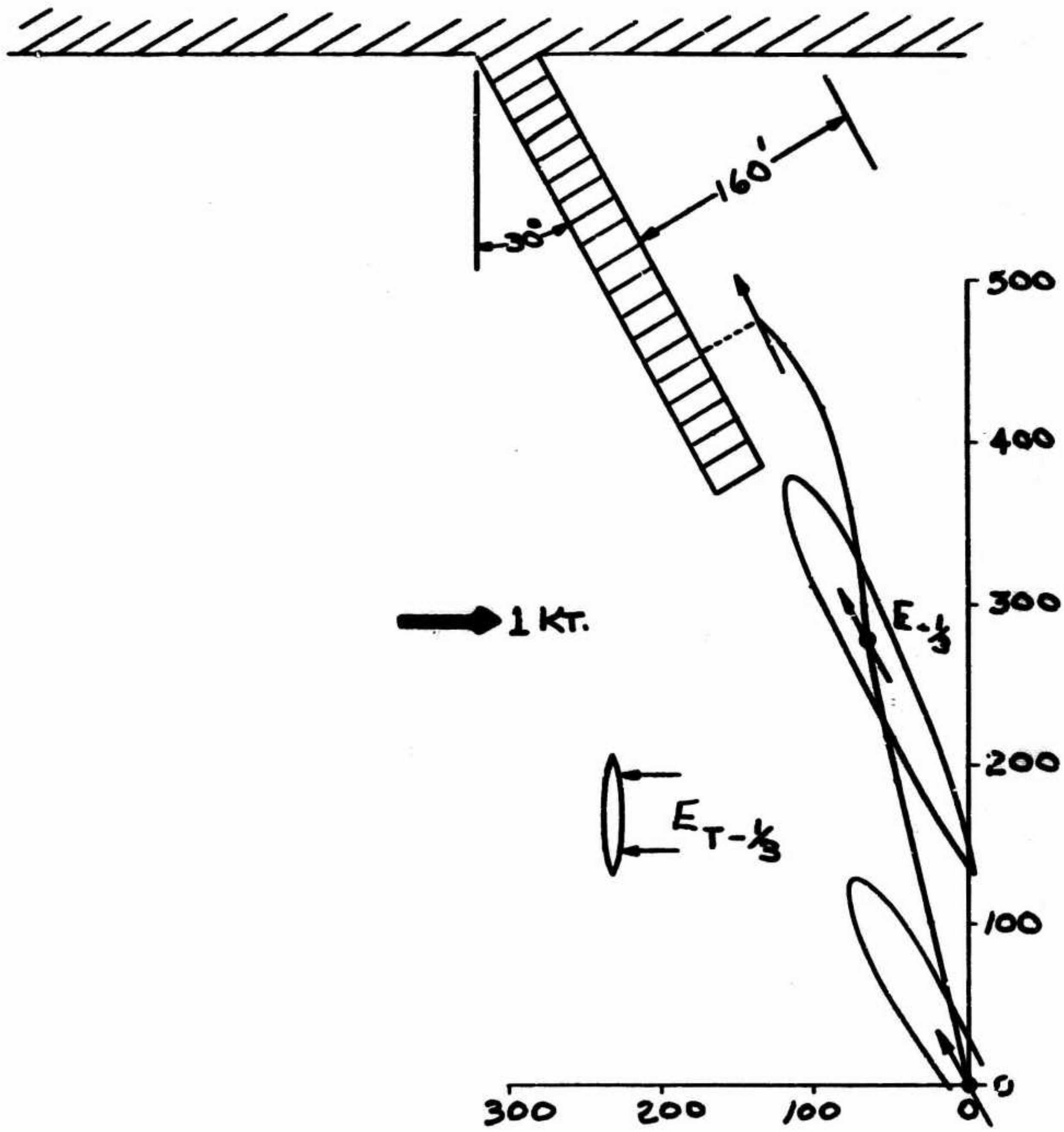

Figure 22 SSN 637 type submarine; port landing in 1-kt ebb current; pier orientation 30°.

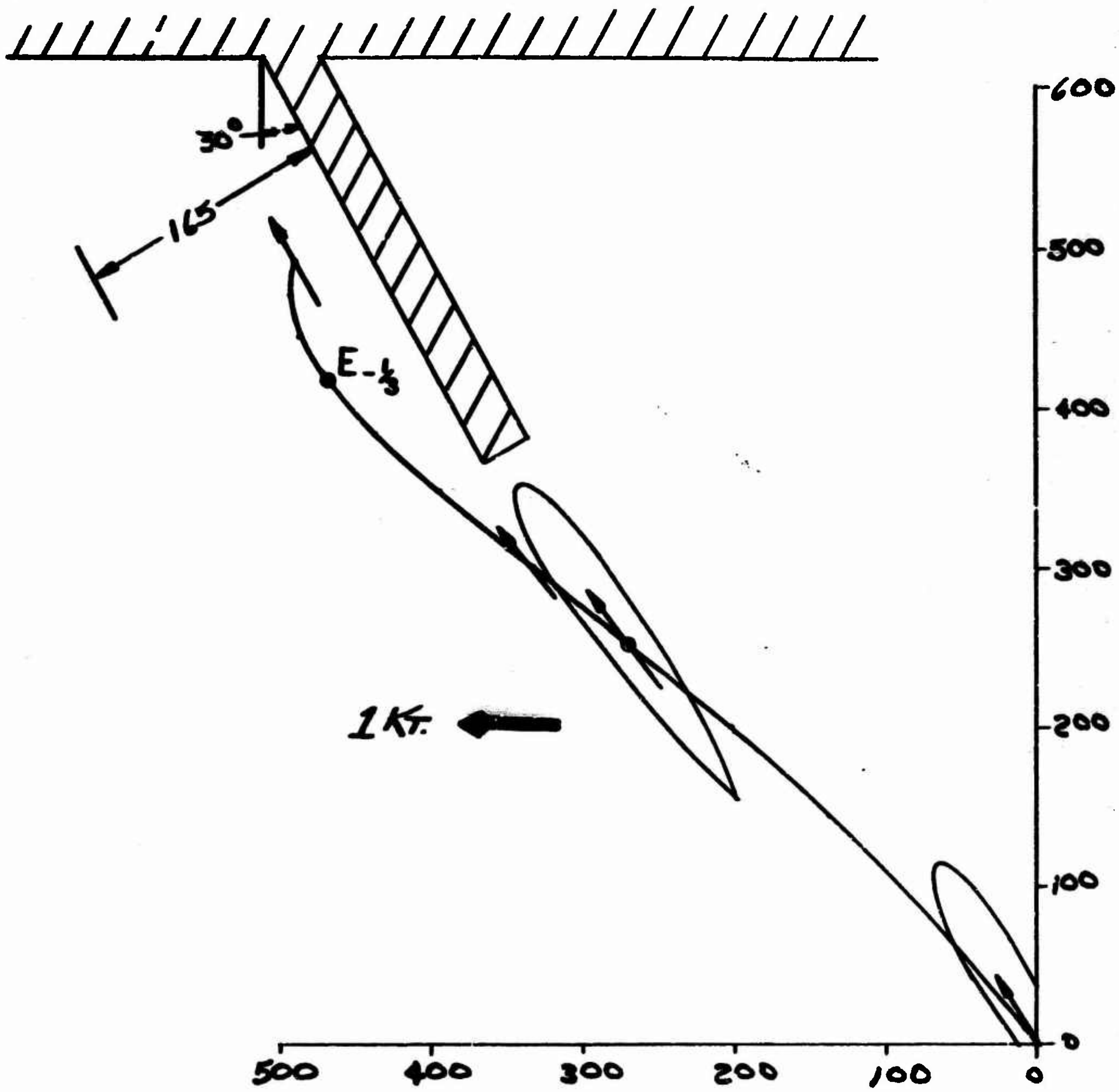

Figure 23 SSN 637 type submarine; starboard landing in 1-kt.flood current; pier orientation 30°.

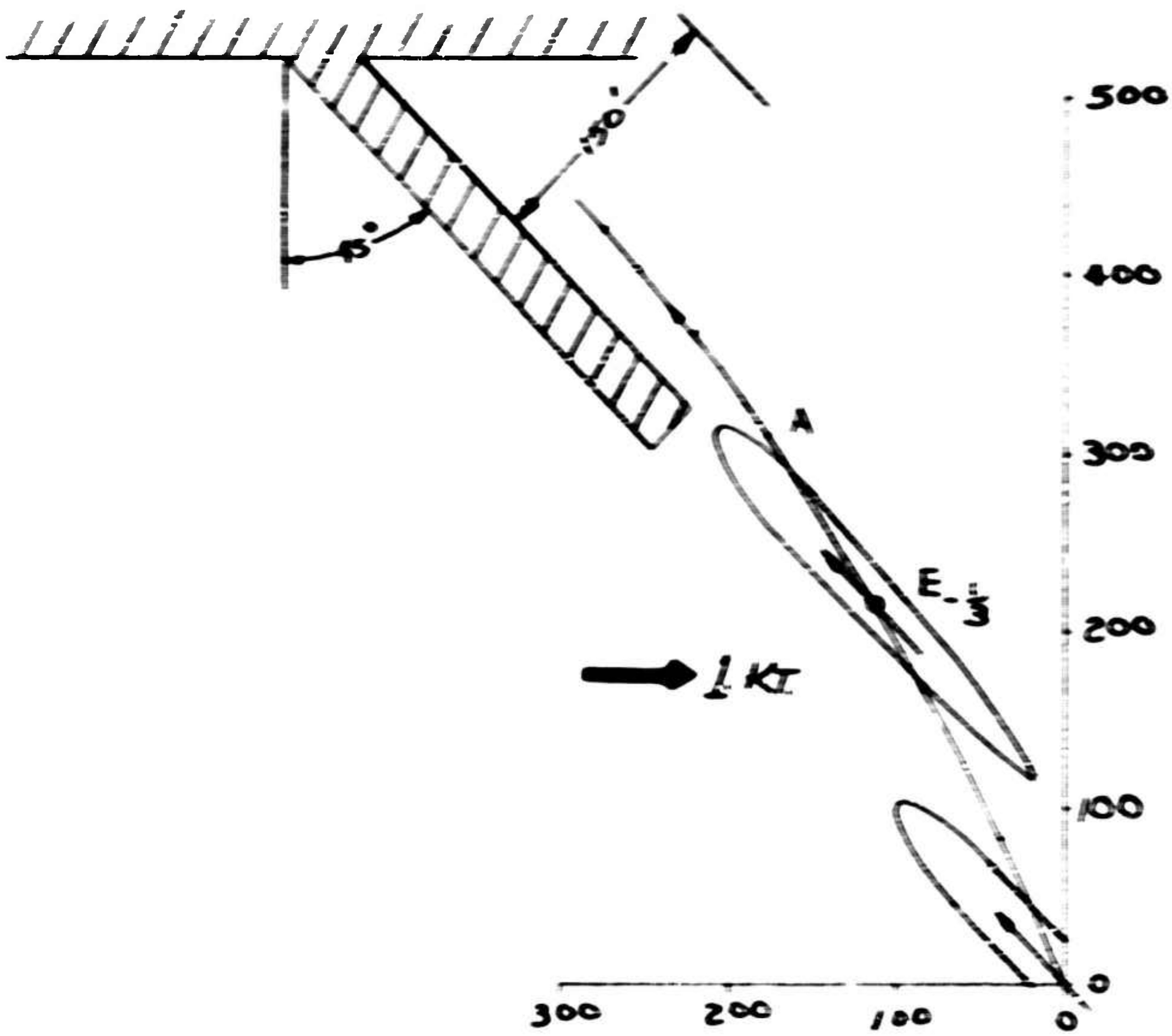

Figure 24 SSN 637 type submarine; port landing in 1-kt ebb current; pier orientation 45°.

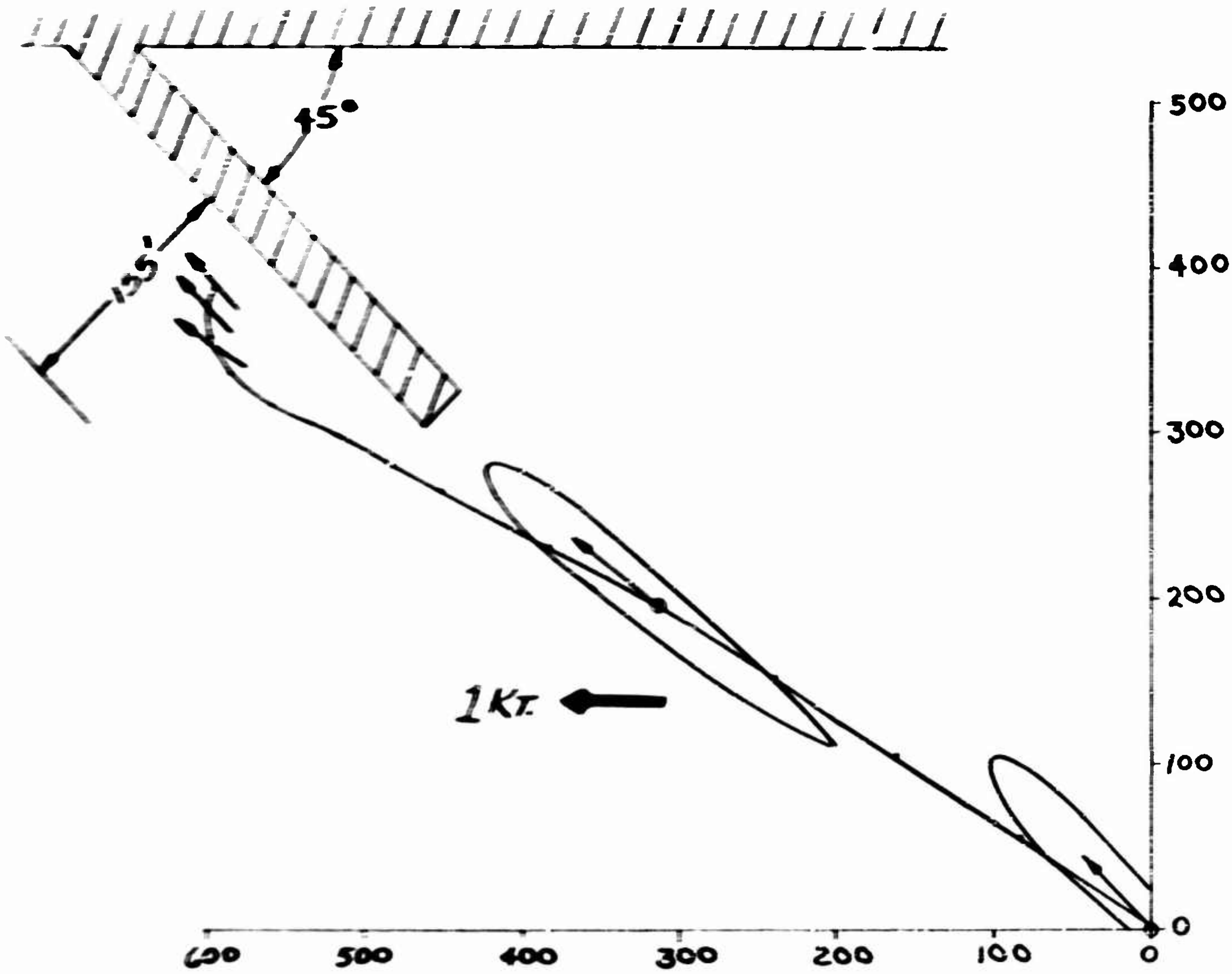

Figure 25 SSN 637 type submarine; starboard landing in 1-kt flood current; pier orientation 45°.

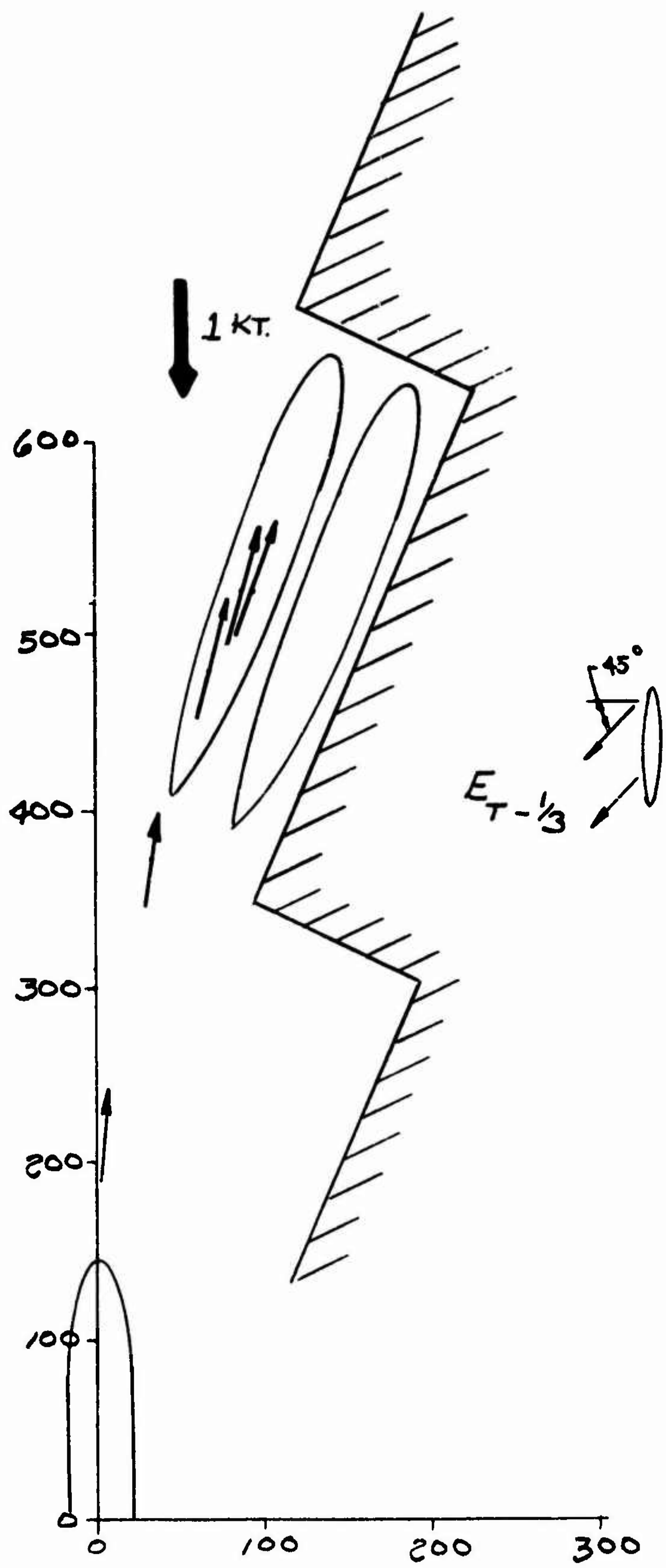

Figure 26 Sawtooth berthing of SSN type submarine in 1-kt head current; case a.

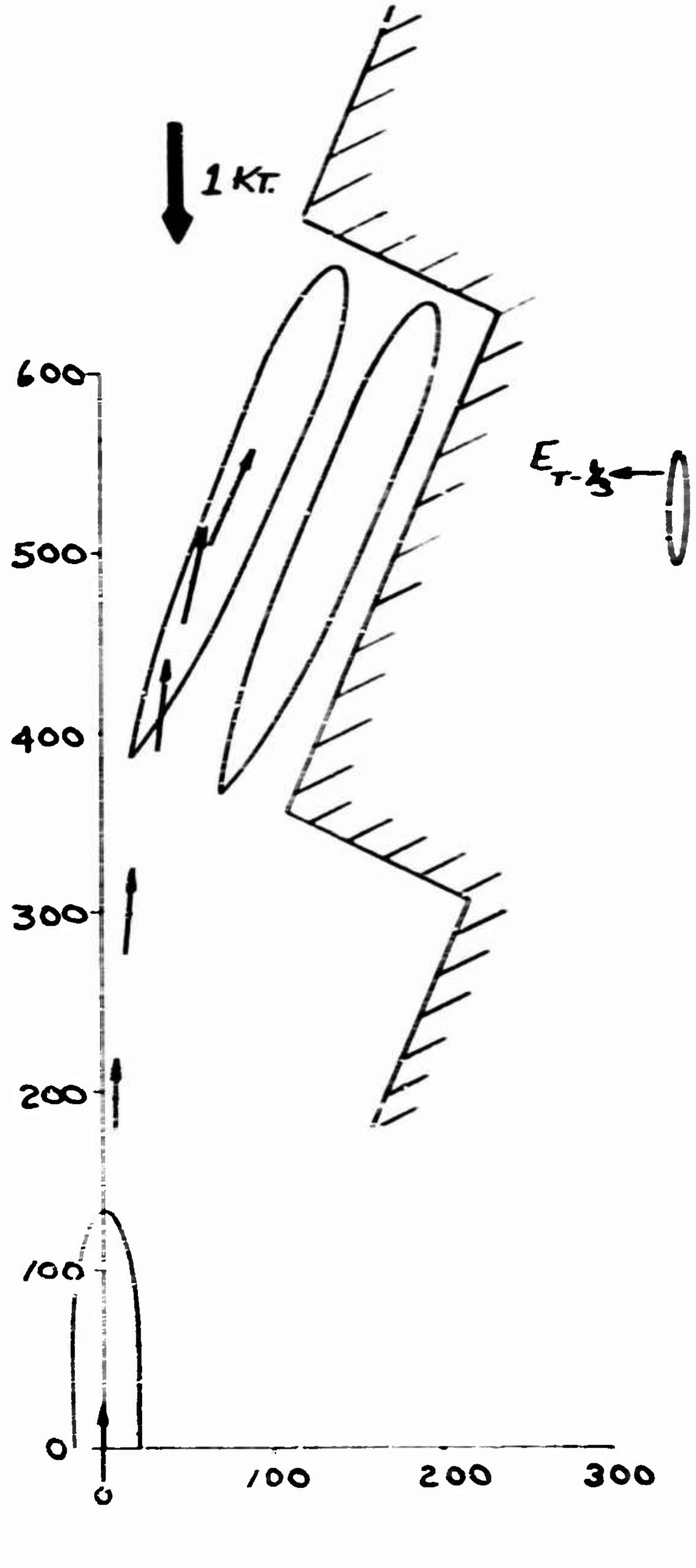

Figure 27 Sawtooth berthing of SSN type submarine in 1-kt head current; case b.

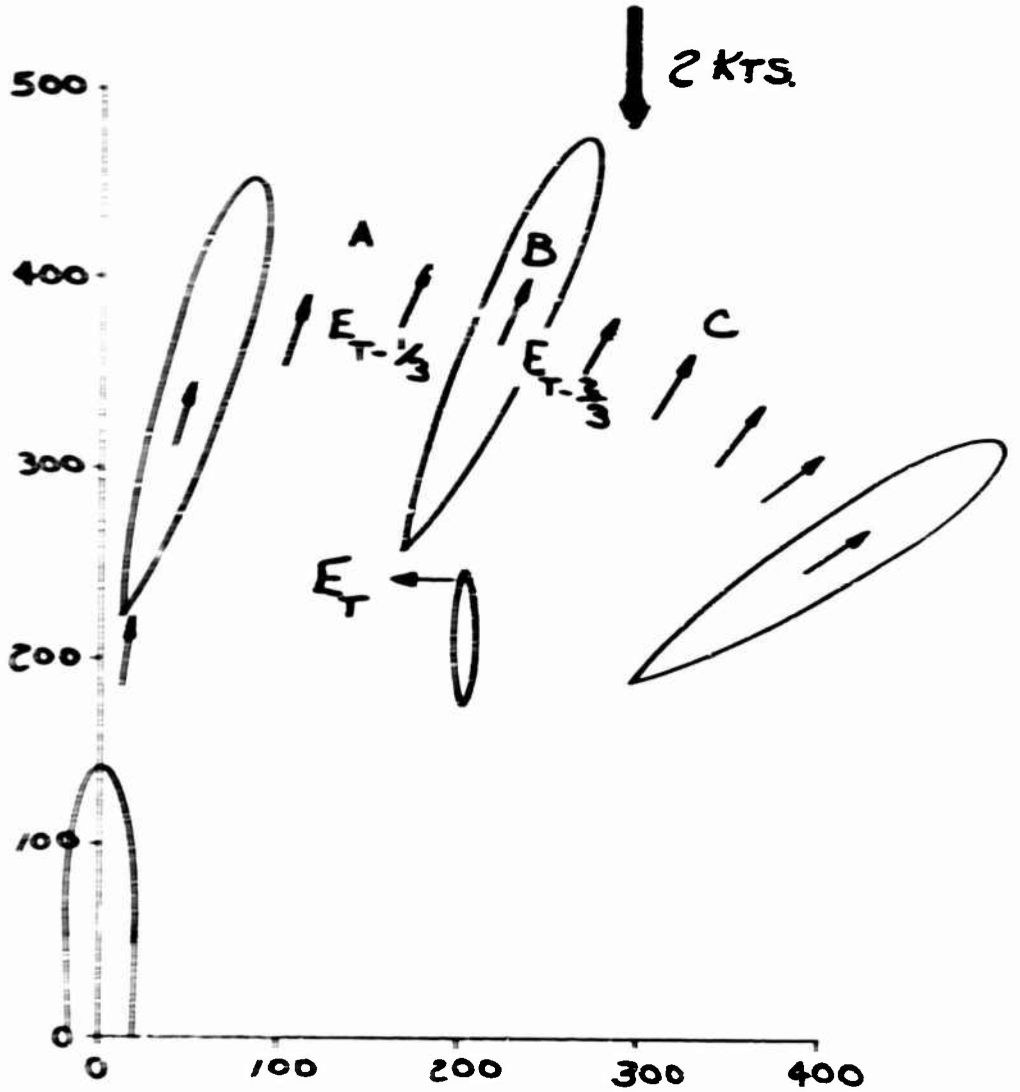

Figure 28 Unsuccessful sawtooth berthing of an SSN type submarine in a 2-kt head current.

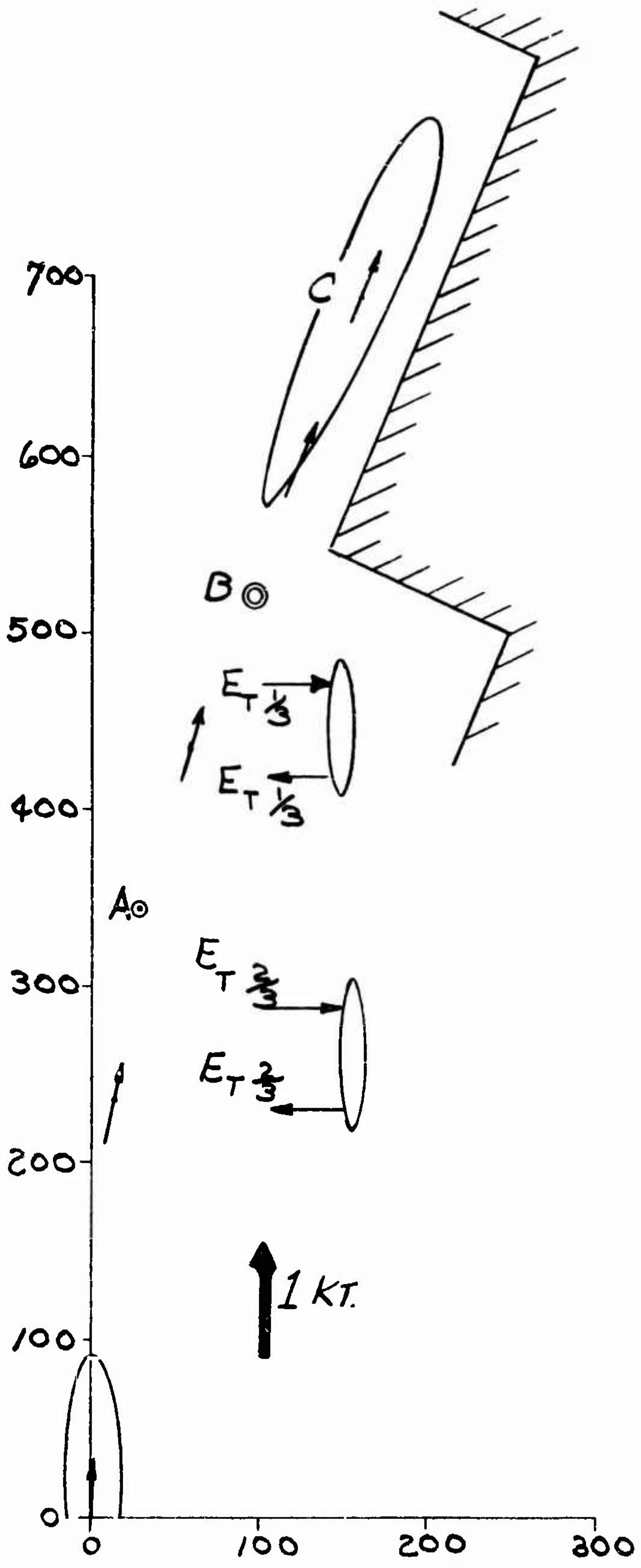

Figure 29 Sawtooth berthing of SSN type submarine in 1-kt following current.

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13 ABSTRACT

The problem of developing an optimum waterfront design for berthing nuclear submarines at the New London Submarine Base is treated primarily as an operational problem involving the interaction of the submarine with the physical environment of the channel. Preliminary investigation revealed that, of all the contributing elements, the presence of tidal currents is the single greatest deterrent to achievement of a successful landing. With due consideration of physical environment, servicing and operational logistics, and practicality of implementation, it is deemed feasible to develop a berthing arrangement that will satisfy all of these constraints. To evaluate the effectiveness of the proposed solution, a computer simulation experiment, of submarine landing, is developed and a parametric study is undertaken. Results show the optimum pier orientation and slip width appropriate to the present waterfront design. Additional experiments show that, for nuclear submarines, a sawtooth berthing arrangement is superior to the optimum conventional layout.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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analog computer simulation						
submarine surface trajectories						
pier orientation						
optimum slip width						

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