Closure on Survival Time

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ABSTRACT

The paper tries to dot all the i's and cross all the t's as far as survival time is concerned. It demonstrated a number of points, 1° for flooding cases with deficient stability, survival time is a random quantity with exponential distribution, the mean value of which is solely dependent on the sea state at the moment of collision, 2° half-an-hour survival tests (in full scale) were adequate for deriving the survival s factor, 3° the complement of the index 1−A is the same as the probability of capsizing during 30 minutes, 4° the required index R should be urgently increased well above the level 0.90, particularly for passenger vessels, and 5° the new SOLAS 2009 should be prevented from entering into force, as it diverges from available knowledge.

KEYWORDS

Survival/capsizal time, damage survivability, probabilistic subdivision regulations

INTRODUCTION

The paper was triggered off by reference [0], dealing with a very complex phenomenon as the capsize time, termed also as survival time. The authors' way of perceiving this issue is, however, unnecessarily complicated. They are right in saying that there are many parameters affecting the complex behaviour of the damaged ship in waves, and hence the survival time. However, all these parameters affect primarily the capsize band, where probability P of surviving (during 30 minutes) varies from one to zero. Once the capsize band has been fixed, probabilistic properties of survival time are also fixed. The capsize band was identified for the first time in 1995 in the "Nordic" project, set up in the wake of the "Estonia" disaster [0].

For given flooding and loading condition probability $P = P(H_s)$ is a function of the sea state only. The matter is discussed in my book on "Subdivision and damage stability of ships" [0] and also in the recent publication in Marine Technology [0], unmentioned in reference [0].

UNDERSTANDING THE SURVIVAL TIME

Survival time is a random quantity, the distribution of which depends solely on the probability P (though P itself depends on a number of parameters). For given sea state and damage scenario, i.e. for given probability of survival P the mean value of survival time is given by a simple equation:

$$t_s = 15\,(1+P)/(1-P), \qquad (1)$$

in minutes. If H_s varies, P varies and so does the average survival time. It can be proved that survival time is distributed according to the exponential distribution and for P = 1, it is infinite. Inside the capsize band, where P < 1, capsizing is a matter of time. That is, sooner or later the ship will definitely capsize.

In reference [0] survival time was identified by numerical tests for a ropax vessel, assuming SOLAS 90 worst damage case. The results were presented in the form of a graph, reproduced in Figure 1, in which survival time varies in a definite range, instead of the infinite one. The reader may have some doubts if the capsizal time is understood properly in this reference. For all flooding cases for which s = 1 the time to capsize should be infinite, if H_s is equal to or smaller than 4 m. For the ship investigated in reference [0] this is obviously not the case. Although the ship meets SOLAS 90 criteria, it is capable of surviving only sea states up to 2 m. If this is the case, reference [0] provides invaluable proof that SOLAS 90 criteria and the current formulation for the s factor have nothing to do with reality. Both are then meaningless. The former should no longer be used, whereas the latter should be modified before SOLAS 2009 becomes reality.

If we talk about survival time we mean the same case of flooding repeated indefinite number of times in the same sea state (but with different realizations). It is assumed that the probability P of surviving is the same each time and depends only on the sea state. The random nature of capsizing is attributed to the random nature of water accumulation on the vehicle deck.

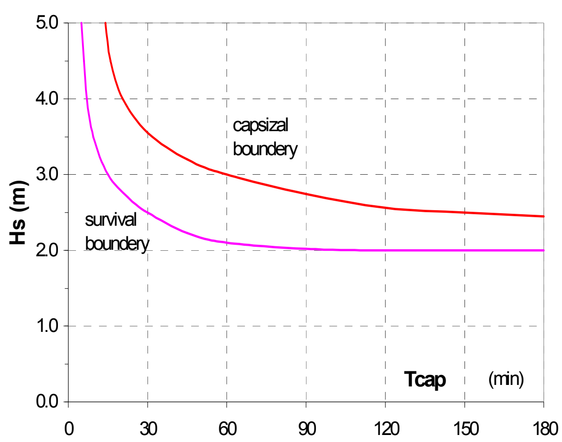

Figure 1. Time to capsize vs. significant wave height for the ship investigated in reference [0] (original Figure 4)

Consider indefinitely long experiments whose duration time is notionally divided into 30-minute segments. It is reasonable to assume that probability of surviving in each segment is the same and equals P. This probability could vary only in the case of progressive flooding. Such a sequence of tests, with a constant probability in each trial, is termed as a Bernoulli trial process.

In such a case probability of surviving n segments equals $F = P^n$. Hence, probability of capsizing at the end on the n-th segment equals $1-F$. In other words, the CDF for capsizal (survival) time equals $1-P^n = 1-\exp(n\ln P)$. Replacing n by a continuous variable x = t/30, we get

$$\mathrm{CDF} = 1 - e^{x\ln P}. \tag{2}$$

If a new constant $\lambda = -\ln P$ is introduced, then

$$\mathrm{CDF} = 1 - e^{-\lambda x}. \tag{3}$$

The average value of survival (capsizal) time for the exponential distribution equals $t_s = 30/\lambda = -30/\ln P$ (in minutes). Equation (1) for the mean survival time has been derived assuming that probability of capsizing in each segment is equally distributed, which is not fully true. It is easy to check, however, that for P > 0.5 differences are negligible between the two estimates of the mean survival time.

Note that for a high P survival time is very sensitive, e.g. for P = 0.85, t_s = 185 minutes, whereas for P = 0.90, t_s = 285 minutes. This means that in such cases accuracy of measurements significantly drops. In other words, the problem becomes ill conditioned.

Substantial work on survival time has been carried out at Strathclyde University, see, for instance, references [0–0], in which Bernoulli trial process was extensively explored. Considerable evidence has been presented during ongoing an EU SafeDOR project showing that Bernoulli model is indeed verifiable, although direct experimental data are scarce. The most recent publication that touches the subject matter with explanations and examples is contained in reference [0].

In the light of the above considerations, it is difficult to understand Figure 1. In particular, the two curves above H_s = 2 m seem to be clearly wrong. The ship in damaged condition can capsize in any time from zero to infinity, with the exponential distribution of probability. Figure 1, however, suggests that the time to capsize is from a definite range, with a minimum and maximum value, depending on the sea state, which seems to be conceptually wrong. There is no reason for such a definite range. If this is true, then the Bernoulli trial process is flawed. Meanwhile, this process compares well with experiments, as shown in reference [0].

Whenever we deal with multidimensional random quantities, it is very important to differentiate between marginal and conditional distributions. The two distributions can be very different. In both cases, however, the survival (capsizal) time is a random quantity varying from zero to infinity. For this reason Figure 1 in unclear for the reader and worth clarifying.

Leaving aside how survival time is understood in this figure, it is worth remembering that the time to capsize has two aspects: design and operational. The former is directly accounted for in the s factor, understood as the average of the probability P with respect to the sea states at moment of collision. By definition, probability that in case of a collision survival time is equal to or greater than 30 minutes is identical with the subdivision index A. Further, probability that survival time is infinite (i.e., the ship will not capsize), denoted by A_1, equals the sum of p_i for all cases of flooding with $s_i = 1$. Surely, $A_1 < A$.

Needless to say that this theorem holds when the factor s is rational, embedded in the mechanism of ship capsizing in waves, that is to say, in the SEM [0–0], [0]. The current s factor, however, is embedded in wishful thinking, remote from reality.

When a collision has happened the compartment flooded, the loading condition and the sea state are fixed, which defines the probability P, and hence, the distribution of survival time. When P = 1, the time to capsize is infinite. How to provide relevant information for the shipmaster, aided his decisions during the crisis, is another matter.

CONNECTION TO THE SUBDIVISION INDEX A

The survival (capsizal) time is directly related to the index of subdivision A. For given flooding case and sea state CDF of survival time depends only, as discussed earlier, on the probability P of surviving in given conditions for 30 minutes, given by

$$\mathrm{CDF}(t) = 1 - P^n, \qquad (4)$$

where n = t/30, where time t is in minutes and can be treated as a continues variable. Note that equation (4) is identical to equation (2). The above describes the conditional distribution of time to capsize for a given sea state and has chiefly the operational meaning. If the above probability is averaged with respect to sea states at the moment of collision (we remember that P for given flooding is a function of the sea state), we get the marginal distribution of the time to capsize for given flooding:

$$\mathrm{CDF}(t) = 1 - \mathrm{E}(P^n) = 1 - s_n, \qquad (5)$$

where $s_n = \mathrm{E}(P^n)$ is the s factor based on n times longer duration of tests. The above average equals the CDF of sea states at the moment of collision taken for the median value or higher quantiles of the critical sea states [0]. It would be worth clarifying, which distribution of time is presented in Figure 1? If the marginal CDF for survival time is further averaged with respect to flooding cases, we get the marginal CDF for survival time for the whole ship:

$$\mathrm{CDF}(t) = 1 - \mathrm{E}(s_n) = 1 - A_n, \qquad (6)$$

where A_n is the index of subdivision based on the s_n factor, accounting for longer duration of tests. As can be seen, the marginal CDF of the time to capsize is the same as the complement of the index A to a value 1. Such an interpretation of the index was unknown earlier.

For a given ship, the CDF(t) is fixed. When the index A is calculated using s factors based on 30-minute tests, then 1−A means nothing else than CDF at t = 30 minutes, that is to say, 1−A means probability of capsizing within 30 minutes. Using s factors based on longer duration of tests does not change probability of capsizing within 30 minutes.

Hence, if A = 0.8 (which is very high according the current standards), then the probability of capsizing within 30 minutes equals 20%, so high that it shames me to communicate this fact to the travelling public. Increasing the required index is therefore of the highest priority, before SOLAS 2009 becomes reality – a good reason for raising the ALARM! Otherwise, the new convention may become obsolete before it enters into force.

As can be seen, extension of the duration of tests has no dramatic influence on the s factor. For flooding cases with s = 1, survival time is infinite. Therefore, the higher the A-index, the greater number of flooding cases with infinite surviving time. What matters for the safety of ships is, therefore, the level of A-indices required by the regulations. Survival time is chiefly an operational issue.

CONSEQUENCES

In the light of the foregoing the existing safety standards are definitely inadequate, despite the official position of MSC. Therefore, Vassalos was completely right raising the alarm about SOLAS 2009 [0]. To shed some light on the matter, consider the average index of subdivision for the whole fleet A to be 0.80 (in fact, this is much less), then the probability of capsizing within 30 minutes equals 0.20, too high to be taken seriously. Assuming that each year on average one collision happens, then at every five years we can expect a catastrophic collision, surely unacceptable for the travelling public.

The probability that during a period of five years no collision happens equals 1/e = 0.368 (which results from the Poisson distribution). For a period of 10 years this figure drops to $1/e^2 = 0.135$, which means a high probability of having at least one catastrophic collision during a decade. If the required index R is not raised, having a collision with a high number of victims is just a matter of time. Who will then tell the stricken families that such a consensus was reached at IMO? We are treading on thin ice.

I am particularly anxious about the fact that officially nothing can be done at SOLAS 2009 and that the decisions have already been taken. If this is really the case and nothing can be done despite the recent advances in science, then at least the title of the convention could be changed into “The International Convention for the Danger of Life at Sea” – DOLAS 2009. This would then be a healthy compromise, so much advocated during the previous Workshop – deficient standards provided under the right name. Otherwise, we will be deceiving the public, offering substandards as standards.

When DOLAS 2009 enters into force, then everyone sticking to the convention would be aware of the true state of affairs. I do not think it is impossible to change the name of the Convention provided that we realise the real state of affairs, i.e., how thin the ice is on which we are treading. To put the things on the right track, the required index R should be well above 0.90, with the factor s embedded in the physics. Then we can seek a compromise. For high indices it is handier to impose a standard for the ratio A/(1–A), rather than for A.

QUANTILES OF THE SURVIVAL TIME

Going back to Figure 1, which is crucial for making progress, the two curves above H_s = 2 m are sensible provided they are quantiles (percentiles) of survival (capsizal) time, with a fixed protection, i.e., probability of not exceeding given value of survival time. By quantiles it is understood the inverse function of CDF, termed also as anti-CDF. Rewriting equation (3), we get the following:

$$1 - F = e^{-\lambda x}, \tag{7}$$

where F ≡ CDF, $\lambda = -\ln P$, and $x = t/30$. Quantiles are obtained by solving equation (7) versus time:

$$t = 30 \ln(1-F)/\ln P, \tag{8}$$

where t is a quantile in minutes for given F, and P is the probability of surviving (capsizing) within 30 minutes, dependent on the sea state. For that reason, quantiles are a function of the sea state, varying as the inverse of lnP. The same does obviously distance between any two quantiles t_2-t_1. That is, when P approaches one (in this case, when H_s approaches 2 m), the distance between quantiles tends to infinity, whereas when P approaches zero, it converges to zero. Figure 1 clearly supports these observations. It makes sense then assuming the two subject curves are some quantiles of survival time, and it would be worth specifying them. Whether we wish or not reference [0] provides accidentally invaluable proof that survival time in the uncertain zone has the exponential distribution of probability, dependent on probability P, with a range extending (theoretically) from zero to infinity. This quantity is of basic importance but was not mentioned in [0]. Further, the run of any two quantiles as, e.g. those in Figure 1, could be used in theory for calculating the probability P in the capsize band but practically this is impossible due to the insufficient accuracy of measurements.

Taking two different protections $1-F_1$, and $1-F_2$, equation (8) yields the following

$$t_2/t_1 = \ln(1-F_2)/\ln(1-F_1), \quad (9)$$

which means that the ratio of any two quantiles is constant at the entire range of H_s from the capsize band. That is to say there is a geometrical affinity between quantiles.

COMPARISONS

To see how this theory works, two quantiles for F = 0.1 and 0.9 were plotted in Figure 2 against the results presented in Figure 1, using exemplary run of the probability P, as shown in Figure 3.

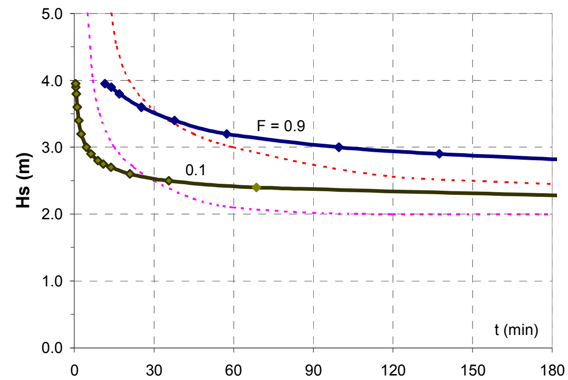

Figure 2. Comparison of quantiles with the time to capsize taken from reference [0]

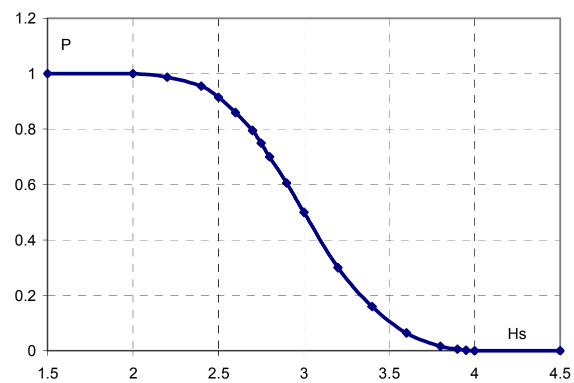

Figure 3. Exemplary run of the probability P versus significant wave height H_s

The lower and upper curves in Figure 2 with F = 0.1 and 0.9 define the time during which probability of capsizing equals 0.1 and 0.9, respectively. For instance, at the sea state H_s = 3 m, $t_{0.1}$ = 4.6 minutes, and $t_{0.9}$ = 99.7 minutes. Obviously, the longer the time, the higher probability of capsizing (or smaller probability of surviving), if damaged stability is deficient. The ratio between the two quantities $t_{0.9}/t_{0.1}$ = 21.9, which results from equation (9). This value is constant and independent of the run of the probability P across the capsize band.

As can be seen, Figure 2 solidly confirms the earlier findings. For t = 30 minutes, the critical wave height varies from 2.5 to 3.5 m, exactly as in reference [0] but the quantiles approach the horizontal asymptote at H_s = 2 m at much slower rate. Whatever the meaning of the two curves in Figure 1, they should not stretch out beyond the level H_s = 4 m. It is worth remembering, however, that quantiles as such have no particular meaning for the design of ships. They have mainly an operational aspect.

CONCLUSIONS

Based on the results and arguments presented in this paper the following conclusions can be drawn:

- for flooding cases with deficient stability, time to capsize is a random quantity with exponential distribution, the mean value of which is solely dependent on the sea state at the moment of collision
- for flooding cases with the factor s = 1, survival time is indefinite
- half-an-hour survival tests (in full scale) were adequate for deriving the s factor
- the index A is the same as probability of surviving a collision with time longer than 30 minutes
- the required index R should be urgently increased above the level 0.90, particularly for passenger vessels, and
- the new SOLAS 2009 should be prevented from entering into force, as it diverges from available knowledge.

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