APPLICATION OF DYNAMIC V-LINES TO NAVAL VESSELS

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ABSTRACT

Damage stability criteria for UK Naval warships include a dynamic allowance for heave and roll in the damage condition. These allowances have been included in the criteria as a prescribed value. The values for this allowance are based on Sarchin and Goldberg's work. Advances in time-domain simulation have allowed dynamic modelling of damaged vessel motion to be investigated. This paper reports on work undertaken to establish a new dynamic standard for UK Naval ships. The paper also defines a methodology for undertaking an assessment of the vessel to ensure compliance with the new dynamic standard.

Keywords: *V-Lines, dynamic, motions, damaged, stability*

1. INTRODUCTION

Damage stability criteria for UK naval warships include a prescribed allowance for the vertical and roll motions known as the V-Line criteria. The V-Line criteria define the level up to which watertight structure is required. While the height of the watertight structure is essential to the survivability of the vessel it is also a cost driver both during build and through life.

The use of V-Lines as a method of ensuring that internal bulkheads do not fail due to water pressure in the damage condition was outlined by Sarchin and Goldberg (1962). They proposed that an allowance above the static damage waterline was required to account for dynamic motions. Sarchin and Goldberg proposed that an allowance of 4ft (1.22m) was used for vertical motions. This allowance approximates to an Upper Sea State 3 wave height. To account for roll, a heel angle requirement was introduced that varied according to ship size. Both of these allowances were based on experience of ships in service at the time rather than derived.

This concept was adapted by the UK Ministry of Defence as follows:

- Vertical motion allowance of 1.5m;
- Roll allowance of 15 degrees.

The application of these allowances are illustrated in Figure 1.

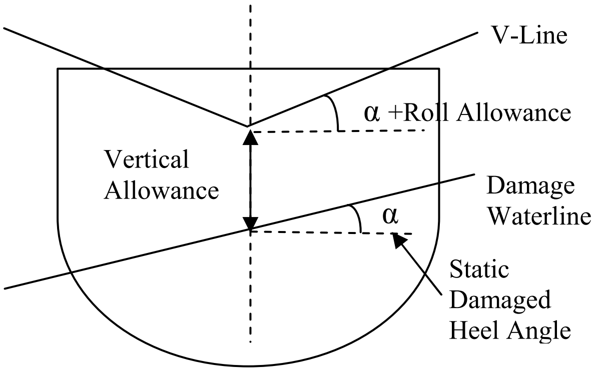


Figure 1. Derivation of V-Line.

It is believed that the UK allowances were changed from those proposed by Sarchin and Goldberg to reflect a slightly higher Sea State 4 and to remove the link between roll allowance and displacement.

The use of these allowances on recent projects has raised the following questions regarding their applicability:

- Is a Sea State 4 a realistic assumption?
- Are the allowances currently in use sufficient?
- Do modern hullforms react in the same way, in a seaway as those the standard is based on?
- Is a single value applicable for all ship types/sizes?

This paper presents the work done that answered the above questions and the development of a new standard. This paper is split into four distinct phases:

- Determine what Sea States the RN currently operates in.
- Determine how often the current V-Lines were exceeded on a selection of ships.
- What standard should be applied to new ships.
- Presentation of an example ship.

2. SEA STATE DETERMINATION

To determine the probability of RN vessels being in a certain sea state a database was built up of reported sea states from RN and RFA vessels. This database contained information from 1968 to 2000 for 76 different ships of a variety of different types.

Table 1 shows the resultant probabilities of being in a sea state along with the upper and lower boundaries for the sea states.

The results in Table 1 show that RN ships spend approximately 95% of their time in a Sea State 5 or less. It can also been seen that RN ships only spend approximately 45% of their time in a Sea State 3 or less as used by Sarchin and Goldberg's method. Therefore suggesting that both the Sarchin and Goldberg allowance and current UK MOD allowance are insufficient for the Sea States as experienced by UK MOD vessels.

3. CURRENT EXCEEDANCE LEVELS

In order to determine the current exceedance levels (i.e. the amount of time that the water is above the current V-Lines) a dynamic time domain modelling package called FREDYN was used. This package has previously been used to undertake an initial investigation into the V-Line criteria by Peters and Williamson (2004). In their paper they assessed the dynamic motions for 3 types of ship and detailed the methodology and assumptions used to produce the data. Their data has been combined with additional assessments of other ship types using the same methodology to assess the current exceedance limits and develop the new dynamic standard.

Table 1. Sea State Probability.

	Sea State							
	0-2	**3**	**4**	**5**	**6**	**7**	**8**	**>8**
Significant Wave Height Lower Bound (m)	0	0.5	1.25	2.5	4	6	9	>14
Significant Wave Height Upper Bound (m)	0.5	1.25	2.5	4	6	9	14	>14
No of Data Points	13992	97637	75302	43657	12832	2819	424	37
Probability %	5.67	39.58	30.52	17.70	5.20	1.14	0.17	0.01
Cumulative Probability %	5.7	45.3	75.8	93.5	98.7	99.8	99.9	100

For this work a total of six types of ship in various loading and damaged conditions were assessed using FREDYN. Each case was run for a simulated period of time for between 4 and 8 headings and in Sea States 3-5. The analysis recorded the percentage of time during the run that the points on the bulkhead being assessed were immersed by water. The assessment points were set up in three vertical lines; one on the centre line and one to port and starboard. On each of the three lines, points were set at intervals of 0.2m starting at the baseline as shown in Figure 2.

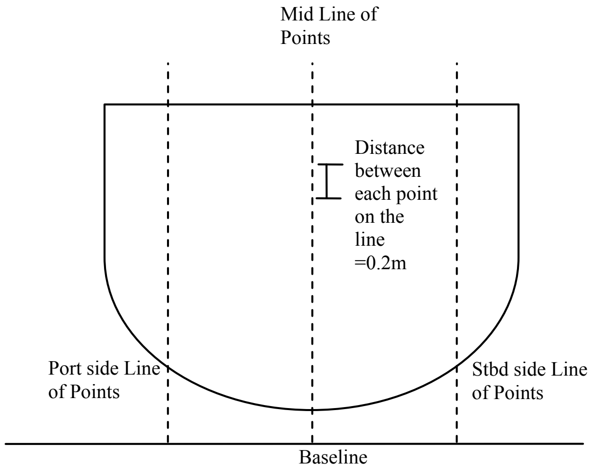


Figure 2. Point Locations.

From the FREDYN results for each damage case the percentage time spent immersed for each point on each bounding bulkhead was found for the desired heading for each sea state and speed. In addition the maximum time spent immersed from all headings was also determined. An example set of data is shown in Table 2.

Table 2. Example Data Results for One Bulkhead and Sea State.

Water Height	**% Time Point Immersed**			
	Head Sea	**Beam Sea**	**Stern Quartering**	**Max**
3.6	90	91	90	91
3.8	85	86	85	86
4.0	82	83	84	84

A graph of the percentage time over the water height against the water height can then be plotted for each heading and for the maximum as shown in Figure 3. In this case the maximum line is a combination of the zero and 45 degree heading results.

Using these graphs the percentage time that the current V-Lines are exceeded can be determined (the intersection of the maximum

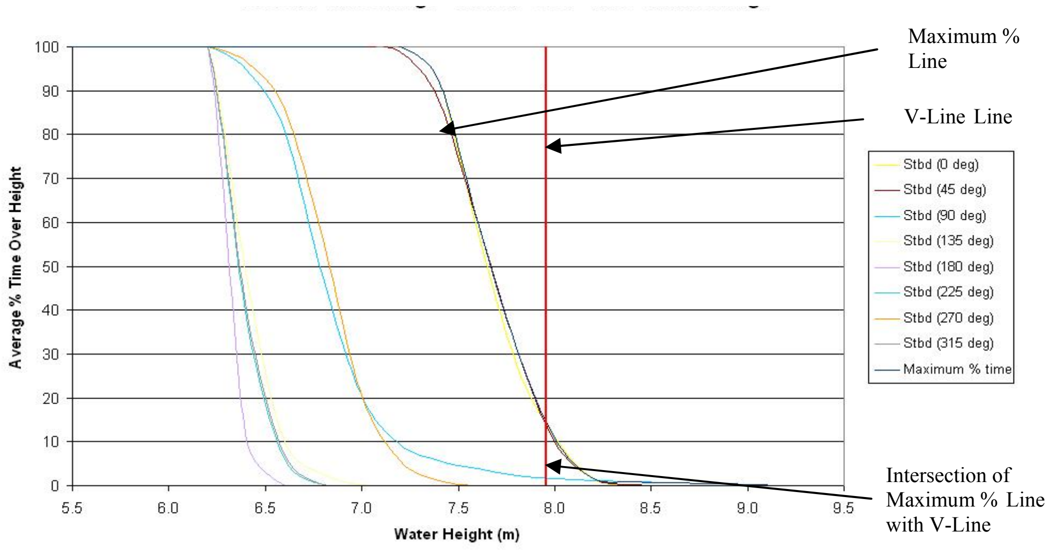


Figure 3.Example Percentage Time Plot.

percentage time curve with the V-Line height). In Figure 3 it can be seen that for this case the V-Line is exceeded approximately 14% of the time. The value at which the V-Line would have to be set so that the water never exceeded it can also be seen (intersection with x –axis). In this case the V-Line would have to be set at 9.1m above baseline.

By repeating the procedure outlined above for all the Sea State 4 results the current exceedance values can be found. The three lines of points (port, mid and starboard) are analysed separately, as the water height will be different for each. This also allows the vertical motion and roll allowances to be investigated separately.

Table 3 shows that for all the vessels assessed the current V-lines on the centreline would be exceeded, on average 15% of the time in the damage condition in a Sea State 4.

Table 3. Exceedance Value in a Sea State 4.

Average % time for Zero exceedance of V-Line in a Sea State 4 for all Assessed Ships		
Centreline (Vertical Motion)	**Port (Roll)**	**Stbd (Roll)**
15	0	4

It can also be seen that the V-Line away from the centreline is rarely exceeded. This indicates that the apex of the current “V” shape is too low and the sides too steep.

The results also displayed significant variation in the percentage exceedance for each of the different ship types therefore suggesting that a single allowance for all ship types as proposed by Sarchin and Goldberg and UK MOD is not appropriate.

4. DYNAMIC STANDARD

As stated the results of the FREDYN analysis showed that the current prescriptive standard did not offer an appropriate level of protection and that a static approach could not be applied across a range of different hullforms.

In addition it has been shown that the RN frequently operate in environmental conditions worse than a Sea State 4 (See Table 1).

A new standard has therefore been proposed that requires the new design to meet a minimum target for the frequency that wave action causes the damage waterline to exceed the design limit. This exceedance limit was set at a target of 5% for both vertical motion and roll allowances, i.e. for 95% of the time the damaged waterline will not exceed the limit.

The decision to use a 5% exceedance limit was based upon the observed shape of the curves as typified by Figures 3 & 4. The majority of the curves show a very steep gradient down to the area of 5-10% time exceedance and then a very slow drop off to 0% time exceedance. Therefore, the use of 5% provides an adequate level of protection without overly penalising the design for low probability events.

The vessel will have to meet this exceedance limit in a Sea State 5 with the waves coming from any direction and with the ship stationary. These parameters are based upon the assumption that the most critical stage is immediately after damage - at which point the vessel is likely to be stopped with no control over the vessel's heading. Based on the data in Table 1 designing to a Sea State 5 gives a high probability that the ship will be in that sea state or lower when damaged.

For vessels that purely operate close to shore a lower Sea State may be acceptable due to the lower probability of the vessel being exposed to higher sea states.

4.1 Application of the Dynamic Standard

Vertical Motion

The centreline results of the dynamic analysis for the bulkhead are plotted as shown in Figure 4. A line is drawn across from the 5% time to the intersection with the maximum curve, as show in Figure 4. The water height at this intersection gives the minimum height for the apex of the V-Line (12.85m in Figure 4) for a 5% exceedance limit.

Roll

The methodology for calculating the roll allowance is exactly the same as that for the vertical motion, except that the port and starboard lines are used instead of the centreline. Obviously the line which gives the maximum height above baseline is used.

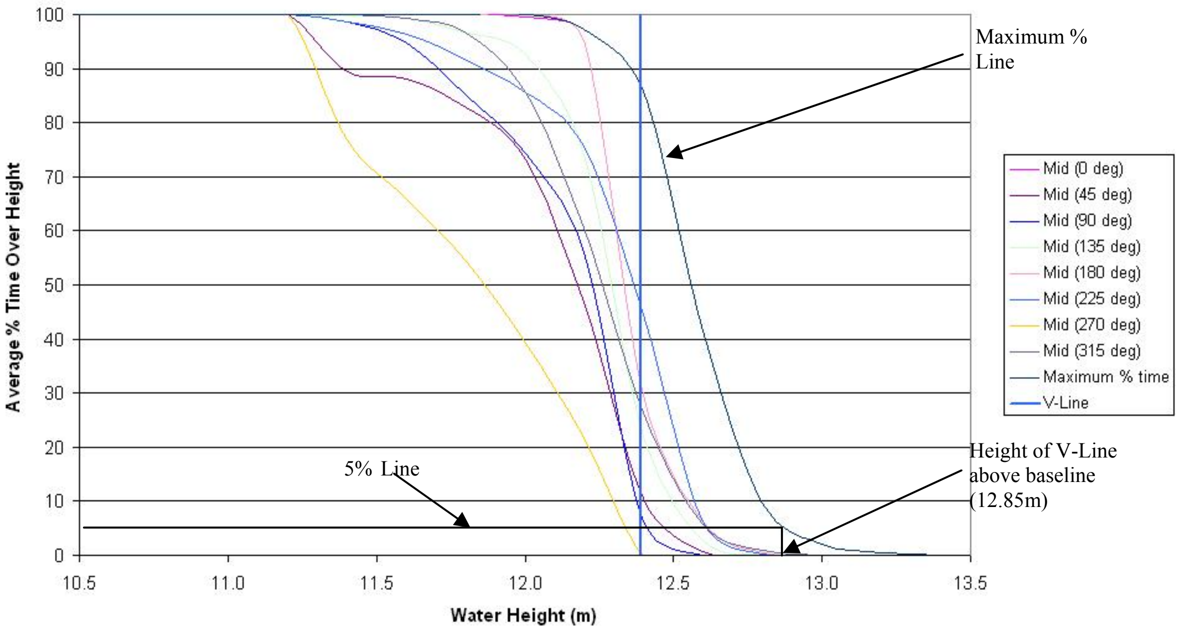
The new V-Line can then be drawn on the bulkhead using the vertical motion value as the apex and the slope provided by the port/starboard height measurement and its transverse offset, see Figure 5.

Application of the standard

The above method is used to find the two heights above baseline (centreline and port/starboard value) for each of the vessel's bulkheads. To simplify the through life application of the standard the maximum value from all the bulkheads is used to create the dynamic standard for that vessel. The maximum value is found by taking the maximum of all the centreline vertical motion heights and the maximum of all the port/starboard heights. An equivalent angle can be calculated using these two values and the offset from the centreline at which the port/starboard line has been taken.

4.2 Prescribed Values

Although the dynamic method will give tailored results for the ship being assessed it will only be possible to do this once the design has reached a certain level of maturity. Therefore for concept designs prescribed values (similar to the traditional approach) are still required so that a basis structural design



Maximum % Line

5% Line

Height of V-Line above baseline (12.85m)

Figure 4. Example Plot showing 5% Exceedance Value.

can be undertaken. A full dynamic investigation can then be carried out against the 5% exceedance values at a later date once the design is sufficiently mature.

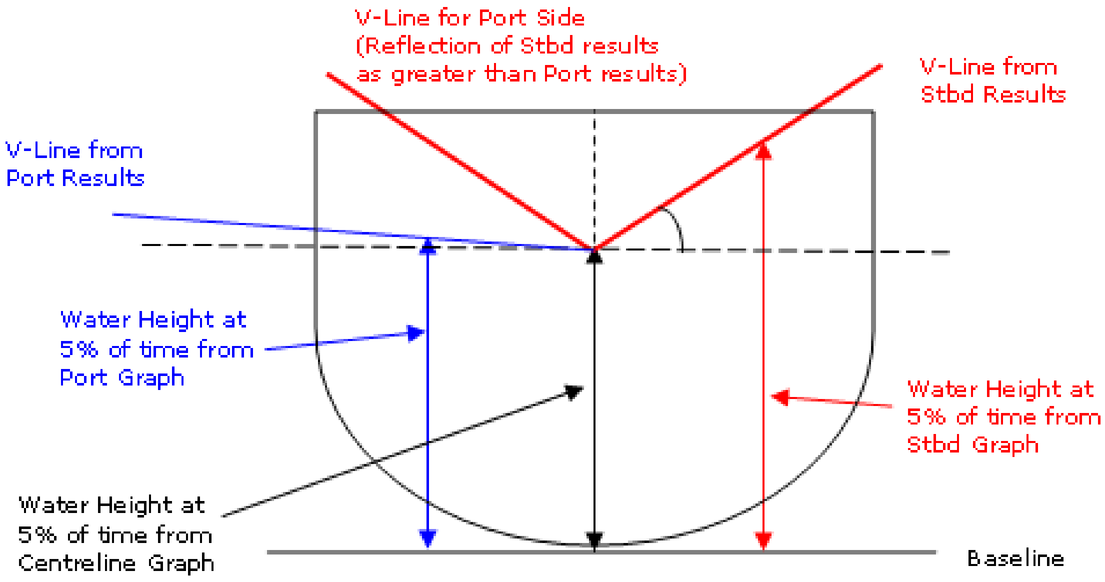


Figure 5 -Derivation of Dynamic V-Line

Vertical Allowance

The prescribed value for the vertical allowance has been found by taking the 5% exceedance value at the centreline and subtracting the height of the damage waterline at the centreline for that damage case. This process was applied to the results for all the damage cases assessed. The actual prescribed allowance to be used is then found by taking the 95th percentile of all these results and is shown in Table 4. Using this method ensures that vessels that are poor sea-keepers will still have sufficient protection but removes any cases that could artificially drive the results.

Equivalent Angle Allowance

The roll allowance is actually influenced by the vertical motions. Therefore the term equivalent angle allowance is used to avoid confusion with the actual roll the vessel was experiencing. To determine the equivalent angle allowance requires deriving the increase in waterline height due to the roll motions from the overall increase due to vertical and roll motions (see Figure 6).

To calculate the equivalent angle exceedance value requires a number of steps (referring to Figure 6):

a. The exceedance value due to both vertical and roll motions (distance AC) is found from the starboard line graphs from the intersection of the 5% exceedance value with the maximum curve.

b. The wave heading that gives the maximum value in a. is noted .

c. The exceedance value for the vertical motions is found from the intersection of the 5% value with the curve for the heading found in b. using the centreline graph (Distance DE).

d. The exceedance value due to vertical motions found in c. is subtracted from the exceedance value due to both vertical and roll motions found in a. This gives the exceedance value that is just due to roll motions (Distance AB).

e. Using the exceedance value just due to roll motions (Distance AB) and the transverse offset of the starboard line the roll motion angle (θ) is found by trigonometry. Finally the static damage heel angle (α) is subtracted from θ to give the equivalent angle due to dynamic motions.

f. The above steps are repeated for the port line results.

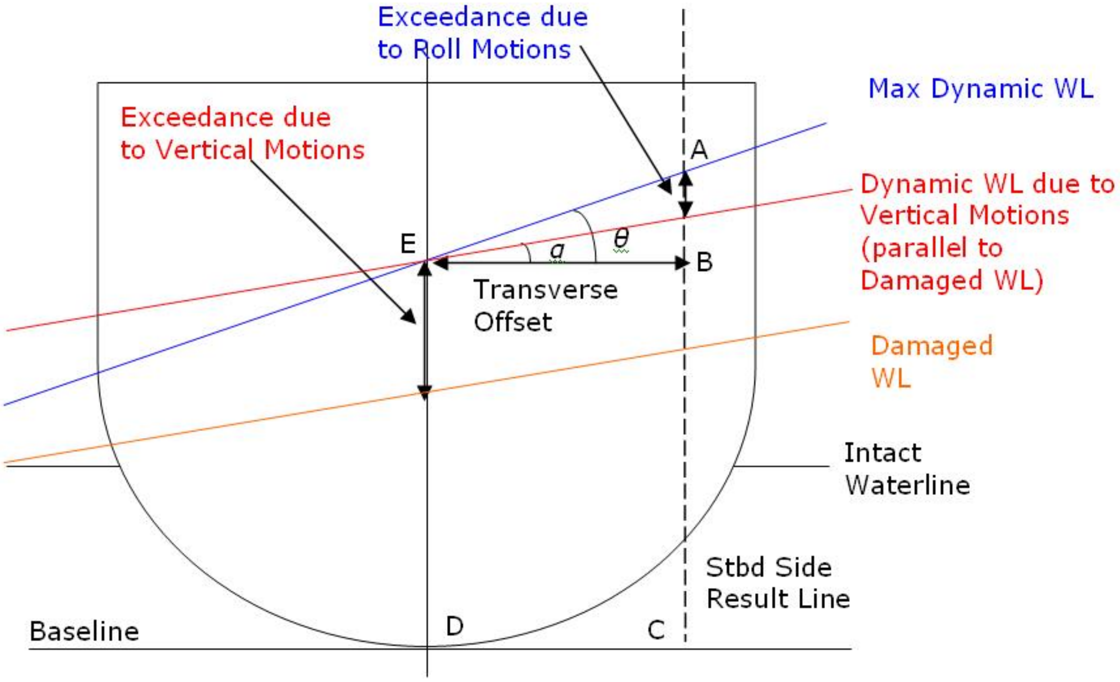


Figure 6 - Derivation of Equivalent Angle

The above steps are repeated for all the damage cases and the maximum of the port and starboard results are used. Again the 95th percentile was taken to remove statistically unlikely events. The final allowance is given in Table 4.

Table 4. 95th Percentile Allowances

Exceedance in a Sea State 5		
	Vertical Motion (m)	Equivalent Angle (degrees)
95th Percentile	2.55	14.25

These results have been rounded to 2.5m for vertical motion and 15 degrees for equivalent angle allowance to provide the prescribed values. This effectively equates to an increase of 1m on the current static V-Line allowances but is for a Sea State 5 rather than a Sea State 3/4.

Further Work on Prescribed Allowances

As more dynamic V-Lines assessments are undertaken the results will be included in a database of results. This will refine the results and eventually it may allow sub-categories of allowances to be created based on different ship types/sizes. Currently this is not considered feasible due to lack of data in each category.

5. APPLICATION TO AN EXAMPLE SHIP

The application of the dynamic v-line approach is given for a small RN vessel. For this vessel 6 bulkheads were investigated in a Sea State 4 and 5. The 5% exceedance water heights for each bulkhead in both the sea states are given in Table 5.

Figure 7 illustrates the position of the current V-Line, the 5% water height exceedance in a Sea State 4 & 5 and the

Dynamic V-Line to be applied for bulkhead E. For this ship bulkhead E is the driving case - hence the Dynamic V-Line is virtually coincident with the 5% Sea State 5 exceedance line.

Table 5. Dynamic Waterline Heights for a Small RN Vessel

	Sea State 4		Sea State 5	
Bulkhead	**Centre Max height**	**Max P/S Height**	**Centre Max height**	**Max P/S Height**
A	4.42	5.61	5.03	5.78
B	4.89	5.73	5.06	5.98
C	4.21	4.58	4.59	5.31
D	4.88	5.48	5.51	5.79
E	4.94	6.06	5.40	6.52
F	4.24	5.51	4.45	5.80
Maximum	**4.94**	**6.06**	**5.51**	**6.52**

Figure 8 illustrates the same information for bulkhead B. Here it can be seen that the 5% exceedance line for a Sea State 5 is below the required dynamic V-line due to the driving influence of bulkhead E.

In both these cases it can be clearly seen that the traditional V-Line is more onerous than the required dynamic V-Line. It is recognised that closer to the centre line the dynamic V-Line is higher than the traditional one. However it should be remembered that these results are for a higher sea state.

6. CONCLUSION

The use of prescribed V-lines to detail the extent of watertight integrity on RN ships is well established. Time domain simulations have shown that the prescribed values used can be overly onerous for the Sea State they are designed to provide protection for.

By using data from existing ships a new dynamic standard has been formulated that depends on the individual vessel's seakeeping and stability characteristics. This change should bring increased post damage capability to the assessed vessels as the V-Lines will be tailored to the ship and match the Sea States that the vessels will be operating in. Although there will be additional analysis costs in the design stage the ability to tailor the V-Lines to the actual ship should provide decreased build and through life support costs.

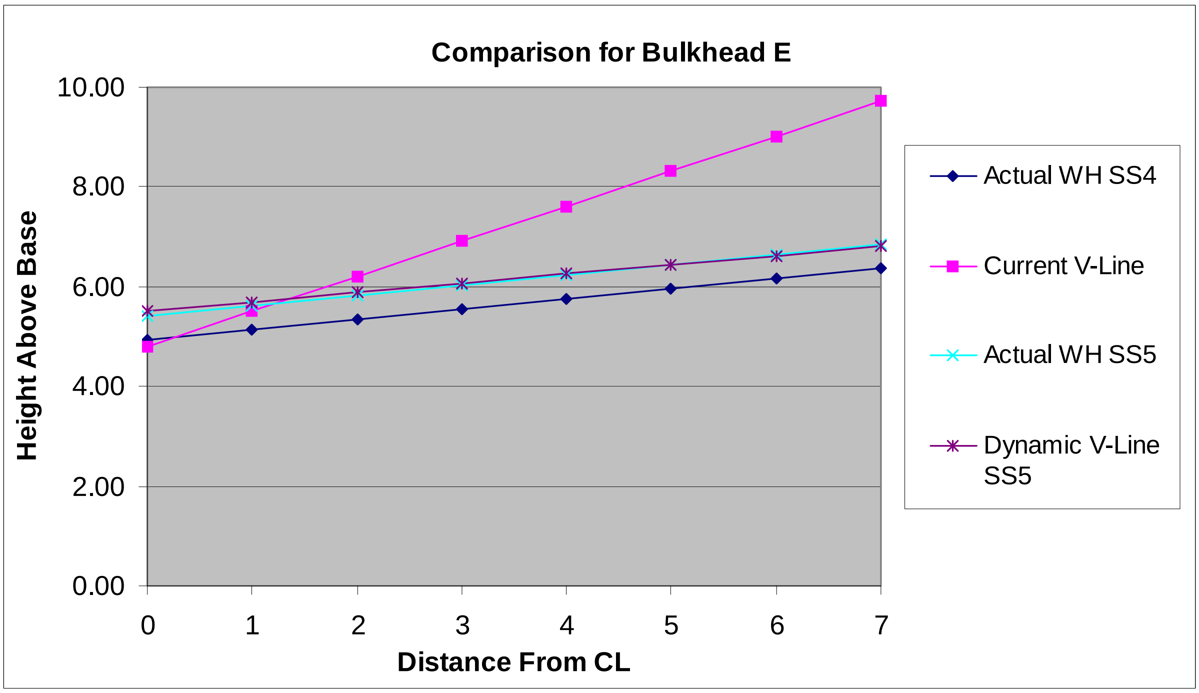


Figure 7. Plot of Water Heights and V-Line Positions for Bulkhead E.

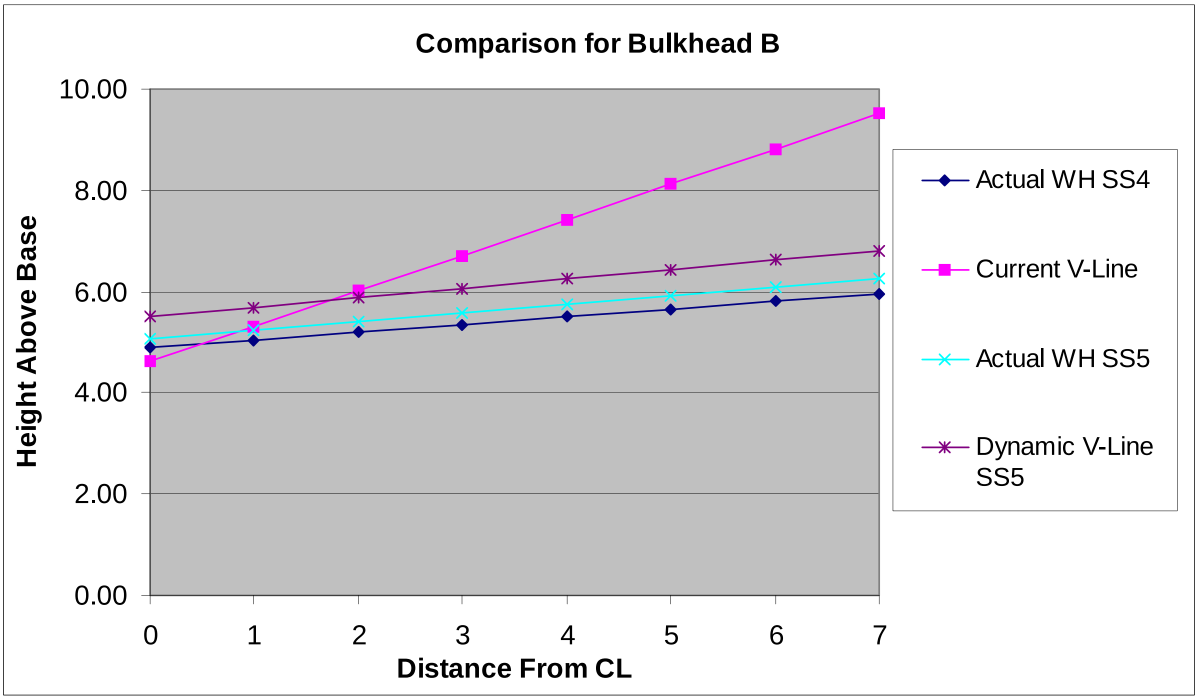


Figure 8. Plot of Water Heights and V-Line Positions for Bulkhead B.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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