UNITED STATES
EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

THE INFLUENCE OF SHALLOW WATER ON
THE RESISTANCE OF A CRUISER MODEL

BY J. G. THEWS AND L. LANDWEBER

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INTRODUCTION

The primary purpose of the work here described was to map out the deviation of shallow water resistance from deep water resistance for a cruiser model. No theoretical explanation of the phenomena of shallow water resistance is attempted. However, various observations of the physical phenomena associated with the motion of the model in restricted water depths were noted both visually and photographically during these tests. These observations are presented together with suggestive interpretations showing the relation between the resistance of the model and the nature of the wave system around it.

DESCRIPTION OF APPARATUS

The work was conducted in the Eighty-Foot Model Basin. The section of this basin is rectangular: seven feet wide and fifty-four inches deep.

In this basin models are towed by a gravity type dynamometer, i.e., the driving effort is obtained from falling weights. The model is initially accelerated by means of a stretched spring and a five pound weight, after which it is driven at constant speed by a selected falling weight. Acceleration in each case must be adjusted to the selected driving weight. Often several runs are required before the balanced condition between accelerated speed and the speed for which the selected weight will tow the model at uniform speed is obtained. On keeping a record of the equilibrium conditions when once obtained, repeat runs are easily made if desired at later times.

The shallow water bottom consists of a series of overlapping built up structural steel sections of welded construction. Each section is as long as the basin is wide less end clearance. They are four feet wide and about three inches deep. The weight per section is about 180 pounds. The material selected was galvanized steel. The finished sections were painted with two coats of aluminum bronze paint. The top surface was covered, in addition, with a black water proof paint for photographic reasons.

The rigidity of these sections is such that each will support a concentrated line load of 200 pounds uniformly distributed along its four foot center line with a maximum central deflection of less than 0.017 inches. It is not reasonable that the four foot model will apply a load of this nature and magnitude. If it did the lift would be more than sufficient to lift the sections and this was at no time observed to happen.

The nature of a bending load applied by a system of ship waves on the submerged sections of this bottom is complex, defying exact analysis. In order, however, to obtain some actual test information in regard to the rigidity of these sections deflection measurements on the approximate center (five inches off on the eight inch longitudinal center line) of one of the sections were made. The exact
center could not be used conveniently because doing so would place the measuring
gear in the path of the model. The measurements were made with an Ames gage the
sensitivity of which was 0.0001 inch.

Figure 1 shows the data obtained. For any given speed the downward deflection
occurs first followed by the upward deflection. This is evident considering that
the bow wave, arriving first, exerts a downward force, and the wake, following, a
negative force. The greatest deflection measured occurred when the model was run in
a three inch depth of water at $V/\sqrt{L} = 0.9$. Its magnitude, from maximum minus to
maximum plus, was 0.0065 of an inch. The rigidity of these sections for this work
is thus verified within these limits.

The shallow water bottom sections are supported in either of two fixed posi-
tions in the basin by means of angles bolted to the inner sides of the basin's walls.
Intermediate depths of water are obtained by raising or lowering the water level.

Since the level of the tow line relative to the basin is fixed a type of
towing bridle had to be used which would not change the tow-trim moment on the model
as the distance between tow line and water level changed. The type designed and
used is shown in Figure 2. The weight of this bridle is part of the model's dis-
placement. The joint between the model and this frame is a pin joint, leaving the
model free to trim except for the small upsetting moment produced by the fact that
this pin is slightly above the model's center of resistance when the model is towed.
This distance, however, is small and moreover constant, so that the comparative re-
sults obtained for the different depths should be unaffected by this factor.

The model tested was a 48 inch cruiser model the characteristics of which
are given in the following table.

<table>
<thead>
<tr>
<th>Cruiser Model No. 3318</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Beam (Maximum)</td>
</tr>
<tr>
<td>Draft</td>
</tr>
<tr>
<td>Wetted Surface Area</td>
</tr>
<tr>
<td>Midship Section Coefficient</td>
</tr>
<tr>
<td>Displacement (Fresh Water)</td>
</tr>
<tr>
<td>Displacement-Length Ratio</td>
</tr>
<tr>
<td>Block Coefficient</td>
</tr>
</tbody>
</table>

The photography of the wave patterns and of the model's trim was accomplished
with a camera using 35 mm. film.

METHOD

The model was run in different depths of water varying from two to fifty
inches and the corresponding speed-resistance data obtained for each depth. Often
a given run represents the result obtained after a number of trial and error runs were made before the proper adjustment between acceleration and driving force was obtained. The attempt was made to have the model run some twenty to thirty feet at constant speed thus indicating that a balance was obtained. This would allow some twenty-five feet for acceleration, about twenty more to gain the balanced condition and then to run at the balance as noted above. See Fig. 3. Even so, for some speeds and depths it was found impossible to obtain a uniform speed for the desired length of run.

The gravity type of dynamometer as used in this work differs from the carriage type in an important respect in some kinds of experimental work. The gravity type tows with a constant force, whereas the carriage type tows with constant speed. Thus the carriage type can measure resistance at all speeds, but the gravity type can measure only those speeds for which equilibrium can be established between the applied force and the model's resistance and speed. This characteristic of the gravity dynamometer was the cause of some of the towing difficulties experienced in the eighty foot basin and there are regions of speed where no results were obtainable. For example, in shallow water work it sometimes happens that there are three possible speeds at which the model will have the same resistance. The intermediate point lies on a part of the resistance-speed curve having a reversed or negative slope.

For the purpose of generating a stable turbulent flow around the model (to produce consistent frictional resistance results) a one-tenth inch diameter wire was placed on the stem. See Figure 4.

The temperature of the water was taken daily. The tests were run during the months of July and August and only small variations of temperature occurred. Thus temperature effects are practically negligible and the total resistances may be compared to determine the effects of shallow water on the four foot form.

The frictional resistance of the dynamometer was measured and the tow-line tension was adjusted daily.

In taking the photographs for measuring trim the camera was placed in a fixed position at one side of the basin slightly above the water level. Trim measurements were made by measuring the change of angle which occurred between a line defined by two white markers on the model and another by white markers on the opposite basin wall. The zero for the trim data was obtained by taking for each condition a photograph of the model at rest in front of the camera's fixed position.

RESULTS

The experimental results of this work are given graphically in Figures 5 and 6. Figure 5 is a plot of the model's resistance, when in various depths of water, against the speed-length ratio \( V/\sqrt{L} \). Figure 6 shows the original data plotted in
terms of specific resistance:

\[(2R/\rho Av^2) \text{ against } V/\sqrt{L}\]

Figure 7 gives graphically the trim measurements for some of the above resistance curves. Figure 8 gives the relation between the values of the ratio \(1.689 V_k/\sqrt{g \, d_o}\) and the depth of the water in terms of model length; where \(\sqrt{g \, d_o}\) is the speed of the shallow water wave of translation in water of depth \(d_o\) and \(V_{k1}\) and \(V_{k2}\) are defined respectively as the speeds at which the tangent line on the steepest part of the shallow water resistance curve intersects the deep water resistance curve and the envelope.

Figure 9 gives a plot showing the percentage increase of shallow water resistance over deep water resistance. This plot is similar to that given by Taylor in his "Speed and Power" on page 75 for the Scout Destroyer.

Figure 11 is a set of faired constant-speed curves similar to those presented by Major Rota in his report on shallow water work in 1900. It also shows a curve, the minimum depth line, giving the least depth for a given speed such that no shallow water effect is observable. Also, superimposed upon this is Taylor's curve for minimum depth given by the relation as indicated in the figure. Taylor says that for speed-length ratios less than 1.0 his formula errs on the safe side. This is verified in Figure 11 for the case of the four foot cruiser model.

The photographic results are presented in Figures 12, 13, 14, and 15. Figure 12 is a set of photographs taken of the model when moving at the different indicated speeds in water three inches deep. Figure 13 is a set of wave profile tracings against the model obtained from trim photographs. Figure 14 is a key to the profiles in Figure 13 for identifying them with their position on the shallow water resistance curve. Figure 15 gives three wave profiles on the cruiser model for different depths but practically at constant speed.

DISCUSSION

As mentioned in the introduction this report is not intended to be a theoretical discussion of the subject of shallow water resistance. However, a number of observations of a general nature were made and where feasible compared with formulas from wave theory.

The wave system generated by a model moving in shallow water appears to be a modified deep water wave system. That this is so is generally recognized in the literature. A description of the nature of this difference, however, has not been found. The following, together with the photographic illustrations presented may serve to throw more light upon this subject. See Figures 12, 13, 14, and 15.

In the following \(d_o\) is the still water depth of the shallow water. The critical velocity is defined by the relation \(v = \sqrt{g \, d_o}\) and is theoretically the
velocity in shallow water of a wave of zero or negligible amplitude.

As the shallow water depth decreases and for velocities less than the critical velocity it was noted, as has been done by others, that the water depth in front of the model becomes greater than \(d_0\) and in the back of the model less than \(d_0\). The frontal increase is \(h\), the height of the wave of translation, and the velocity of this wave is given to a fair first approximation as \(v = \sqrt{g(d_0 + h)}\).

At velocities much below the critical velocity the bow wave pattern resembles the deep water pattern. As speed increases the bow wave system corresponding to the deep water system is present but much less intense. Also, it is noted that waves are formed periodically and run out ahead of the model. As model velocity approaches the critical velocity these waves do not continue to form and run out ahead of the model, and only one, the wave of translation as it is ordinarily referred to, forms in front of the model. In shallow water, then, the bow wave system does not form fully as it does in deep water, and less so as \(d_0\) decreases. Moreover waves from the bow run out ahead of the model or a single wave of translation forms in front of the model and stays with it.

The decrease in depth towards the stern is caused by the high stream velocity (greater than in the case of deep water due to the restricted cross-sectional area produced by the presence of the bottom) necessary to fill in the space vacated by the moving model. Both the wave of translation and the stern waves tend to form with their crest lines at right angles to the length of the basin and the more so the less the depth \(d_0\). The result is a profile as given in Figure 10.

![Figure 10.](image)

It is observed that the model ceases to generate the stern wave system before attaining the critical speed. This is probably due to the fact that as speed increases the stern waves are intensified until they break, due to their running in water of depth less than \(d_0\), and, secondly, because the water at the stern has a velocity towards the rear giving the wave an even greater relative velocity with respect to this water.
On the other hand the bow wave of translation runs into undisturbed water of depth $d_0$. Its speed is greater than the critical velocity by the factor $\sqrt{(d_0 + h)/d_0}$. It was observed that for a given model in a given depth of water there was an upper limit to the speed of the bow wave of translation. When this maximum speed is exceeded the bow wave of translation cannot form. Simultaneously with the formation of the bow wave of translation there appears to be a continued partial formation of the normal deep water bow wave system and an increased planing attitude on the part of the model.

Since deep water wave making resistance is associated with the deep water wave pattern and the typical humps and hollows are caused by the progressive interference that takes place between the bow and stern waves, the modification of this pattern as occurs in shallow water would make the shallow water wave making resistance different from that of deep water.

The formation of the described shallow water waves at speeds below and above the critical speed suggests an explanation of the characteristics of the shallow water resistance curve and its deviations from the corresponding deep water curve. In Fig. 16 are shown diagrammatically deep water and shallow water resistance curves. In the region F is indicated the effect of restricted depth on frictional resistance, the increase being due apparently to the increased stream velocity of the water past the walls of the model, and the intensified shearing action to which the water between the model's bottom and the shallow water bottom is subjected. $V_C$, as above, is the critical velocity, $\sqrt{g \cdot d_0}$. $V_A - V_A'$ is the speed range in which the leading stern wave moves out from under the stern of the model. Neither the speed at the beginning nor the end of this speed range is the critical velocity for the given depth of water as is sometimes thought. The deviation from the critical speed
is shown graphically in Figure 8. As the wave moves out from under the model, the latter is rapidly prevented, for small increases in speed, from recovering energy from this wave to aid its forward motion. When this leading stern wave clears the stern of the model the latter can experience no further loss due to the further recession of this wave and for this reason an additional increase in speed should not show a corresponding rate of increase of resistance above point A as existed below it. Having moved away from the model, the stern wave ceases to influence the model's resistance at higher speeds. This would account for the bend in the shallow water resistance curve at A. The trim curves also show that maximum trim occurs at the speed corresponding to point A.

As noted above, the stern wave system ceases to keep up with the model before the model can exceed the speed of the wave of translation which forms at the bow. The further rise in resistance with speed as shown in the shallow water resistance curve is attributed to the further increase in stream velocity as the speed increases and also to the building up of the wave of translation. For this part of the speed range, as the model's speed increases so does the height of this wave of translation and its speed. However, its height does not increase rapidly enough to enable it to stay with the model as the latter's speed continues to increase. Soon a speed $V_B$ is reached where model speed is equal to $\sqrt{g(d_o + h)}$, and with a small increment in speed the model passes over the bow wave. Then, with the same towing force it runs at a much higher speed.

The speed range defined by $V_A - V_B$ in Fig. 16 decreases as depth increases. According to the equation for the velocity of the wave of translation $V_C = \sqrt{g(d_o + h)}$ this would mean that as the depth, $d_o$, increases the value of $h$ becomes increasingly small in its influence on $V_C$.

The fact that at the higher speeds shallow water resistance is less than that for deep water is attributed as due to the restrictions placed on the formation of the normal deep water wave system and the consequent earlier approach to a planing condition.

The shallow water resistance curves will be noted to form an envelope above the deep water resistance curve. See Fig. 5. The hump in this envelope is of some theoretical interest.

The big hump in the deep water resistance curve for the four-foot cruiser model occurs approximately, according to Figure 6, at a speed such that

$$V_1 = 1.5\sqrt{L}.$$  

The speed of the wave of translation, for a given depth of shallow water is given by

$$V_s = 3.36 \sqrt{d_o + h} \text{ knots.}$$
For the condition where $V_1$ equals $V_2$, it is reasonable to expect a maximum in the envelope of the shallow water resistance curves. It would be a condition similar to resonance in forced vibrations. Equating the right hand members of the above equations and solving for $d_o$ we have:

$$3.36 \sqrt{d_o + h} = 1.5 \sqrt{L},$$

and from this, neglecting $h$

$$d_o = 0.20L.$$

For $L = 48$ inches, $d_o = 9.6$ inches. This value of $d_o$ checks well with that obtained experimentally as is shown on the plot of the resistance curves, Figure 5.

The results given in this work apply strictly to the four foot model. Any extrapolations from these results to full scale ships of similar form have a qualitative rather than quantitative value at this time. Frictional resistance, as usual, would appear to be the offending factor. The separate influences of shallow water upon frictional resistance and wave making resistance has not been determined as far as the writers are aware of. It is recognized, however, that some empirical work along this line has been done. The general observations made in connection with the influence of shallow water on the wave pattern as generated by the model together with the corresponding effects on the resistance of the model should, however, apply directly to geometrically similar conditions on a large scale.

These studies are to be continued in connection with a commercial type of vessel, namely the S.S. CLAIRTON, of which a model thirty inches long is available. It is a full form, and thus, being a good wave maker, should exaggerate the differences between deep and shallow water wave systems.
FIGURE 1. CENTRAL DEFORMATIONS OF SHALLOW WATER BOTTOM UNDER CRUISER MODEL 3518
FIGURE 2. VIEW OF BRIDLE DESIGNED FOR TOWING MODELS
SHALLOW WATER TESTS
WITH
4" CRUISER MODEL 338
WATER DEPTH = 3.0
JULY 2, 1926

FIGURE 3.
FIGURE 4. WIRE ON BOW OF MODEL
FIGURE 5. RESISTANCE CURVES FOR MODEL 3318
FIGURE 6. SPECIFIC RESISTANCE CURVES FOR MODEL 3318
FIGURE 7. TRIM—SPEED CURVES FOR MODEL 3318

The symbols correspond to those used on resistance curves, Fig. 5
FIGURE 8. FOUR-FOOT CRUISER MODEL 3318
FIG. 9. CONTOURS OF CONSTANT PERCENTAGE INCREASE IN RESISTANCE

CRUISER MODEL 3318

\[ \frac{D}{(L/100)^3} = 55.8 \]

\( V \) = SPEED OF MODEL, KTS.
\( L \) = LENGTH OF MODEL, FT.
\( d \) = DEPTH OF WATER, FT.
\( D \) = DISPLACEMENT, TONS.
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\[ F_i \sigma \cdot 10 \]
CRUISER MODEL 3318

LENGTH: 48.0 INCHES
BEAM (MAXIMUM): 5.42
DRAFT: 1.58
WETTED SURFACE AREA: 1.825 SQ.FT.
MIDSHIP SECTION COEFFICIENT: 0.92
DISPLACEMENT (FRESH WATER): 7.82 LB.
DISPLACEMENT-LENGTH RATIO: 55.8
BLOCK COEFFICIENT: 0.547

NOTATION
L = LENGTH OF MODEL IN FEET
H = DRAFT OF MODEL
d = DEPTH OF WATER
V/\sqrt{L} = THE NUMBERS ON THE CURVES INDICATE VALUES OF

FIG. 11. FAIRED CONSTANT - SPEED CURVES
Figure 12: Model 3318 in three inches of water with \( \sqrt{V} \) increasing.
FIG. 13. MODEL 3318 IN WATER THREE INCHES DEEP

TRACINGS OF PHOTOGRAPHIC WAVE PROFILES
The circled numbers correspond to the similar numbers in Figure 13 identifying wave profile with position on the shallow water resistance curve.
\[ V = 2.02 \text{ Knots} \]

\[ d = 50'' \]

\[ V = 2.04 \text{ Knots} \]

\[ d = 6'' \]

\[ V = 1.94 \text{ Knots} \]

\[ d = 3'' \]

FIGURE 15. WAVE PROFILE TRACINGS FROM PHOTOGRAPHS
DEPTH VARIABLE WITH SPEED CONSTANT (APPROX)
APPENDIX I

THE WAVE OF TRANSLATION IN SHALLOW WATER

A wave of translation is one consisting of a single hump and no hollow. See Figure. It travels with a velocity which is determined by its own amplitude and the depth of the water. Theory gives as a first approximation the following expression for this velocity in feet per second:

\[ v = \sqrt{g(d_o + h)} \]

where \( g = 32.2 \) feet per sec.\(^2\), and \( d_o \) and \( h \) are respectively the depth and the wave amplitude in feet. If \( h \) is negligibly small compared to \( d_o \), then the expression becomes

\[ v = \sqrt{g d_o} \]

The form of this wave resembles closely that of the versine. Assuming the similarity the wave may be described by the following expressions, the meaning of the symbols being indicated in Figure.

\[ x = d_o \times \Theta \]
\[ y = h/2 (1 - \cos \Theta) \]
\[ L = 2\pi d_o \]

A few measurements of the speed of this type of wave were made experimentally in the eighty foot basin. Distances were laid off along the basin and the times required for the waves to travel a given distance were measured with a stopwatch. The values for \( v^2/d_o \) are approximately equal to \( g \), which, according to theory, and when \( h \) is small compared with \( d_o \), should be true. The experimental results are given in the table below.
EXPERIMENTAL RESULTS FROM THE EIGHTY FOOT BASIN ON THE SPEED OF THE WAVE OF TRANSLATION

<table>
<thead>
<tr>
<th>Depth in Feet $d_0$</th>
<th>Distance in Feet $S$</th>
<th>Time in Sec. $t$</th>
<th>Velocity Ft./Sec. $v$</th>
<th>$v^2/d_0$ or $g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>20</td>
<td>15.0</td>
<td>1.33</td>
<td>35.4</td>
</tr>
<tr>
<td>0.05</td>
<td>28</td>
<td>21.0</td>
<td>1.33</td>
<td>35.4</td>
</tr>
<tr>
<td>0.10</td>
<td>36</td>
<td>19.0</td>
<td>1.89</td>
<td>35.7</td>
</tr>
<tr>
<td>0.10</td>
<td>40</td>
<td>21.4</td>
<td>1.87</td>
<td>35.0</td>
</tr>
<tr>
<td>0.129</td>
<td>40</td>
<td>18.5</td>
<td>2.16</td>
<td>36.1</td>
</tr>
<tr>
<td>0.129</td>
<td>40</td>
<td>19.0</td>
<td>2.11</td>
<td>34.5</td>
</tr>
<tr>
<td>0.167</td>
<td>40</td>
<td>17.0</td>
<td>2.35</td>
<td>33.2</td>
</tr>
<tr>
<td>0.167</td>
<td>40</td>
<td>16.8</td>
<td>2.38</td>
<td>34.0</td>
</tr>
</tbody>
</table>
APPENDIX II

EXPERIMENTAL RESULTS ON CRITICAL VELOCITY

Speed of Waves of Translation Preceding a Towed Model in the Big Model Basin

The measurements listed below were made by Wm. H. Bowers.

In the table below:

- The model is referred to by number,
- $D$ Model's displacement in pounds,
- $V$ Model's speed in knots,
- $S$ Distance between wave observing stations in feet,
- $t$ Time required for wave to travel $S$ feet in sec.,
- $v$ Speed of wave in feet per second.

<table>
<thead>
<tr>
<th>Model</th>
<th>$D$</th>
<th>$V$</th>
<th>$S$</th>
<th>$t$</th>
<th>$v$</th>
<th>$\bar{V}$ (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2933</td>
<td>2628</td>
<td>2.67</td>
<td>154.5</td>
<td>6.5</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>2933</td>
<td>2628</td>
<td>2.87</td>
<td>154.5</td>
<td>8.5</td>
<td>18</td>
<td>21.0</td>
</tr>
<tr>
<td>2880</td>
<td>2395</td>
<td>2.00</td>
<td>154.5</td>
<td>10.2</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>2880</td>
<td>2395</td>
<td>2.00</td>
<td>154.5</td>
<td>8.0</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>2193</td>
<td>743</td>
<td>4.00</td>
<td>154.5</td>
<td>7.7</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>2193</td>
<td>743</td>
<td>4.00</td>
<td>154.5</td>
<td>9.7</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

Notation in the following is the same as for the above. $S$ is the distance from the starting position of the model to the observation station. $t$ is the time from the start of the model from rest to the time of arrival of the first wave of translation at the observation station.

<table>
<thead>
<tr>
<th>Model</th>
<th>$D$</th>
<th>$V$</th>
<th>$S$</th>
<th>$t$</th>
<th>$v$</th>
<th>$\bar{V}$ (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3043</td>
<td>3.0</td>
<td>284</td>
<td>23</td>
<td>12.4</td>
<td></td>
<td>12.4</td>
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<tr>
<td>3043</td>
<td>6.0</td>
<td>284</td>
<td>23</td>
<td>12.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2962</td>
<td>4.5</td>
<td>284</td>
<td>19</td>
<td>15</td>
<td></td>
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<tr>
<td>2962</td>
<td>6.4</td>
<td>284</td>
<td>20</td>
<td>14</td>
<td></td>
<td>13.5</td>
</tr>
<tr>
<td>2962</td>
<td>6.45</td>
<td>284</td>
<td>22</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2962</td>
<td>7.05</td>
<td>284</td>
<td>24</td>
<td>12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The slower wave speed in this second set of results is attributed to the fact that the first wave does not leave the model as a wave of translation until some time after the start. 17 ft./sec., is the critical velocity computed from basin dimensions.
HALF SECTION OF THE U. S. MODEL BASIN

Dimensions in Feet and Inches

Area of cross section \( A \)=192 sq. ft.
Width of section \( B \) = 21.33 ft.
Average depth \( A/B \) = 9.00 ft.

The critical velocity is given by

\[ v = \sqrt{\frac{g}{A/B}} = 17.0 \text{ feet/sec.} \]