MOVING 800 PEOPLE ACROSS THE DECK

by Samuel Halpern

A question that was raised during the British Wreck Commission enquiry into the loss of the SS *Titanic* had to do with people being asked to move to one side of the ship in order to correct a noticeable list to port that developed very late in the sinking process. When *Titanic* first struck the iceberg at 11:40pm along her starboard side she immediately started to take in water. She soon developed a 5° list to starboard (Figure 1) that was seen on the ship's inclinometer in the wheelhouse within the first 10 minutes.[1]

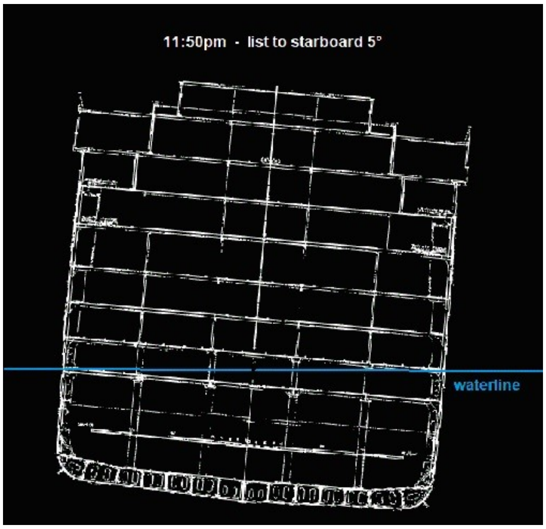

Fig. 1 – Cross section of *Titanic* looking forward with 5° list to starboard.

However, that initial list to starboard did not remain. By about the time that the loading of lifeboat No. 9 was being completed, around 1:15am, *Titanic* had just about righted herself, and was no longer carrying a noticeable list despite being noticeably trimmed down by the head at the time.[2] Some time after that, a slight list to port started to develop. By the time that lifeboat No. 10 was launched, around 1:50am, the list to port had reached about 10° as ascertained by the 2½ to 3 foot gap that passengers had to jump or be carried across in order to get into the boat.

By around 2:05am, the time that Second Officer Lightoller launched collapsible boat D, the list to port had reached closer to about 15° as shown below in Figure 2. (This was based on eyewitness observational data of the water level seen from where boat D was being launched.)

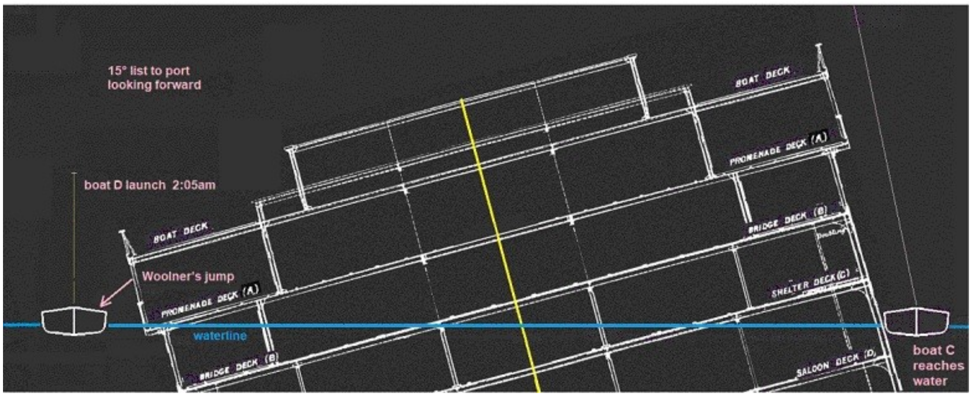

Fig. 2 – *Titanic* looking forward showing 15° list to port around 2:05am.

At the US Senate investigation onto the loss of the SS *Titanic*, *Titanic*'s Second Officer Charles Lightoller was asked a series of questions by Senator Smith:

> Senator SMITH. Were the passengers on those decks instructed at any time to go to one side or the other of the ship?
> Mr. LIGHTOLLER. Yes.
> Senator SMITH. What do you know about that?
> Mr. LIGHTOLLER. When the ship was taking a heavy list - not a heavy list - but she was taking a list over to port, the order was called, I think, by the chief officer [Wilde]. "Everyone on the starboard side to straighten her up," which I repeated.
> Senator SMITH. How long before you left the ship?
> Mr. LIGHTOLLER. I could not say, sir.
> Senator SMITH. About how long?
> Mr. LIGHTOLLER. Half an hour or three quarters of an hour.
> Senator SMITH. Before you left?
> Mr. LIGHTOLLER. Yes.

Lightoller left the ship just before she broke in two. A half-hour before he left would have been around the time that lifeboat No. 10 was still being loaded, around 1:45am. At that time the ship was listing about 10° to port, and was trimmed down by the head about 5° (see Figure 3).

Fig. 3 – *Titanic* trimmed down by the head about 5°.

On day 20 of the British Wreck Commission's enquiry into the *Titanic* disaster, naval architect Edward Wilding from Harland and Wolff, the builders of *Titanic*, was asked:

> 20932. Q. [Mr. Laing] Another reference occurs in the evidence to the effect of moving the people across the deck with the view of correcting the list. I think Mr. Lightoller [*Titanic*'s Second Officer] told us about that; have you made any experiment to see what effect moving a number of people would have?
> A. [Wilding] We have made an experiment to test the ship's stability, and from that it is possible to calculate the effect.
> 20933. Q. I think you have made the calculation?
> A. Yes.
> 20934. Q. Moving 800 people through 50 feet would right her 2 degrees?
> A. About 2 degrees.

From the questioning it is obvious that Mr. Laing had the result of Wilding's calculation already in his hand. But how did Wilding actually obtain that result? He only referred to making some calculation based on first obtaining the ship's stability.

By "ship's stability" it is assumed that he meant obtaining the ship's metacentric height, also known as the ship's GM, under a given state of flooding. What state of flooding did Wilding assume, if any? That we cannot be certain of. However, when Second Officer Lightoller was questioned on day 12 of the British enquiry about the effectiveness of moving a large group of people across the deck to straighten out the list to port that had developed, he had this to say:

> 13944. Q. [The Commissioner] You mean to say the shifting of the passengers on the deck would affect the list?
> A. [Lightoller] Yes, my Lord. At that height, and with that number of passengers, I think it would. Mr. Wilding would be able to decide that.
> 13945. Q. It would have a very small effect, would it not?
> A. I am under the impression the fact of her being low down in the water and the stern higher out of the water it would have more effect than if she were on an even keel under ordinary circumstances.
> 13946. Q. Surely it would have more effect if she were high up out of the water?
> A. I may be wrong, my Lord, but I think it would have more effect with her head down in the water and her stern out - suspended amidships.

It should be noted that Lightoller was questioned eight days before Wilding was called to testify. The state of the vessel being well down by the head with her stern exposed describes *Titanic* as she would appear very late in the sinking process, close to the end, when she had developed that noticeable list to port.

So What Is This "Metacentric Height" Thing All About?

Without trying to get too technical here, a ship's metacentric height provides the naval architect with a simple measure that relates to the leverage arm that is created that will allow the ship to right itself to an upright position if the vessel is somehow tipped a little bit toward one side. To understand this, consider the vessel shown below in Figure 4.

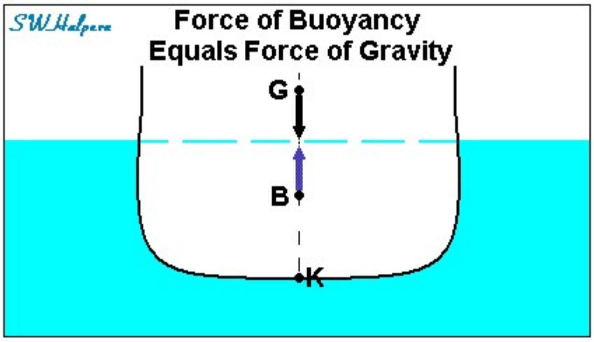

Fig. 4 – Forces on ship while in upright position.

When a ship is at rest on an even keel in calm water, the force of buoyancy (at B) and the force of gravity (at G) are equal and opposite, and lie in the same vertical line as shown in the figure above. The force of gravity is the result of the combination of all downward acting forces including the weight of all parts of the ship's structure, its equipment, cargo, fuel, ballast and personnel. This combined force is the total weight of the ship, and may be considered as a single force which acts **downward** through a single point called the **center of gravity (G)**. This force is equal to the ship's displacement in tons and usually lies on the ship's centerline near the ship's amidships section under normal trim conditions.

The force of buoyancy that keeps the ship afloat is also a combined force that results from the pressure of seawater on all parts of the ship's hull that is acting on the ship below the waterline. Like the force of gravity, the total force of buoyancy can be considered as single force that acts vertically **upward** through a single point called the **center of buoyancy (B)**. It is the geometric center of the ship's underwater body form and lies on the ship's centerline and usually near amidships when the ship is on an even keel. The value of the upward force of buoyancy must equal the downward force of gravity for the ship to stay afloat. Its vertical height above the keel **(K)** is usually a little more than half the draft of the vessel when afloat.

Now a ship may be disturbed from rest by conditions which tend to make it heel over by a small angle.[3] When that happens, the vessel's underwater body form changes shape. The center of her underwater volume is shifted in the direction of the heel which causes the center of buoyancy (originally at **B**) to relocate off of the vessel's centerline and move to the geometric center of the new underwater body form (at **B'**). As a result, the lines of action of the force of gravity (which is straight down) and the line of buoyancy (which is straight up) are no longer acting one directly above the other on the same vertical line, but are acting on parallel vertical lines that are separated from each other in way that the forces want to restore the vessel back to an upright condition as shown below in Figure 5.

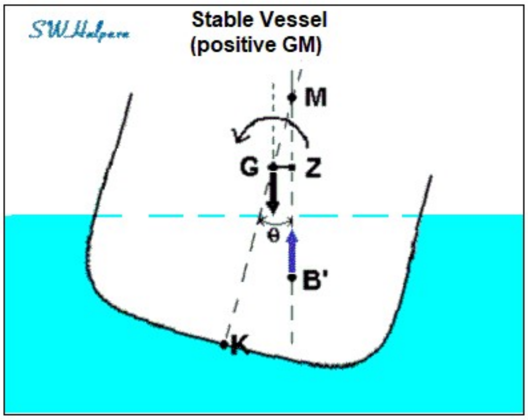

Fig. 5 – Forces on ship when heeled to one side with positive stability.

In the above diagram, the vessel has been tipped to one side producing a small angle of heel (θ). The line where the buoyant force (shown here pushing straight up from the shifted center of buoyancy **B'**) intersects the centerline of the hull is called the metacenter (**M**) point. The distance between this metacenter point (at **M**) and ship's center of gravity point (at **G**) is called the "metacentric height" (or **GM**).

If **M** is located *above* the center of gravity **G**, as shown in the diagram above, the metacentric height is considered *positive*, and the ship is stable in the sense that it will want to right itself back to an upright position. The higher **M** is above **G**, the more stable is the vessel because a larger righting arm (or lever) will be created for a given angle of heel.

The strength of the righting moment, that is the value of torque that is created trying to twist the vessel back to an upright position, is usually taken about the vessel's center of gravity point **G**. It is the product of the force of buoyancy times the distance **GZ** that separates the line of action of the buoyancy force from line of action of the gravitational force as shown above. That distance **GZ** is called the "righting arm" or "righting lever."

Since the force of buoyancy must equal the force of gravity (which equals the total weight of the ship), the restoring or righting moment is simply equal to the ship's displacement weight (**W**) in tons multiplied by the length of the righting arm (**GZ**) in feet.[4] The result will be a measure of the restoring torque in foot-tons.

But what if the point **M** falls below **G** as shown in the diagram below? In this case the metacentric height (the distance **GM**) is considered to be *negative*, and the forces of buoyancy and gravity are located such as to create what is called an upsetting moment, and the ship will want to heel over more and possibly capsize as shown in Figure 6. Clearly, a condition of negative GM is unstable and must be avoided.

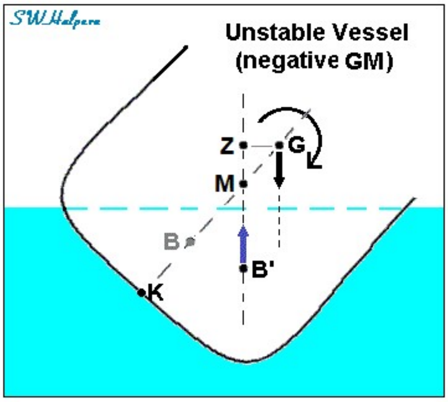

Fig. 6 – Forces on ship when heeled to one side with negative stability.

An unstable condition can come about by placing too much weight high up in the ship, a situation where the center of gravity (**G**) gets above the metacenter (**M**) creating a negative **GM** condition as shown above.

For a stable ship with a positive **GM**, how high **M** is located above **G** also matters. If the metacentric height (**GM**) is too large, the righting arm that develops at small angles of heel will also be very large. Such a ship is considered to be very "stiff" and will tend to roll with a short period and a large amplitude as it tries to follow the slope of any waves that come from the side. This can become very uncomfortable for passengers and crew, especially in a moderate to heavy seaway. On the other hand, if the metacentric height is small, the righting arm that develops with small angles of heel will also be small. Such a ship is considered "tender" and will have a long rolling period, a situation more suited for passengers. However, if the metacentric height is too small, the risk of the ship capsizing in rough weather increases, and it also puts the vessel at risk of developing large angles of heel if cargo or ballast should happen to shift. A ship with a very small but positive GM is also less safe if the ship is damaged because it leaves less of a safety margin against capsizing.

Locations of G, B and M for *Titanic* on the night of April 14th 1912

Values for the location of the center of gravity (**G**), the center of buoyancy (**B**), and the initial metacenter (**M**) for the SS *Titanic* were obtained for the night of April 14, 1912 before the fatal collision with an iceberg occurred.[5] These location are shown in Figure 7 along with their heights above the keel, (**KG**, **KB**, and **KM**). Also shown is how *Titanic* would have appeared if she somehow had been subjected by an outside force crating an angle of heel of $\theta = 15°$ while still in her intact condition.

Prior to the collision, *Titanic* had a **GM** value of 2 feet 7½ inches (2.63 ft), and a displacement weight (**W**) of 48,300 tons after completing about 2/3 of her voyage. If submitted to an external force such that she heeled over by 15° (as shown in Fig. 7), she would have developed a restoring moment of $\mathbf{W \times GM \times sin}\ \theta$ = 35,607 foot-tons of torque to bring her back to an upright position. Again, this holds only for her intact condition, before any accident occurred. Once damaged, with water entering the vessel in several compartments, things become very messy, and the location of **G**, **M** and **B** would begin to change. In that dynamic condition, a complete damage analysis would have to be performed for various conditions of flooding. Such analysis has been done,[6] but is well beyond the scope of what we want to get into here.

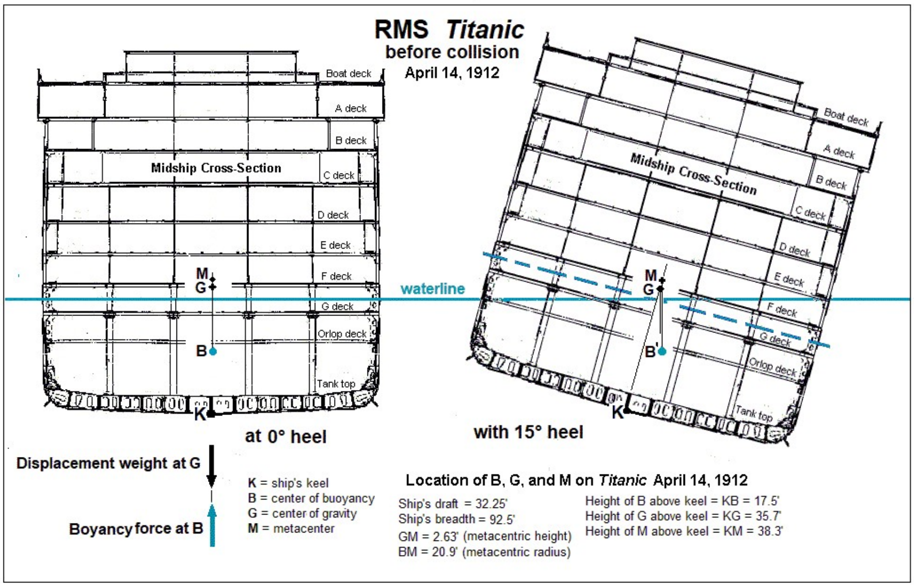

Fig. 7 – Location of B, G, and M on Titanic on April 14, 1912 prior to collision.

So How Did Edward Wilding Come Up With His 2° Change in List?

During his testimony before the Wreck Commission, Edward Wilding presented a serious of diagrams which he called "Flooding by Compartment." These showed the state of the vessel by progressively flooding each watertight compartment, one after another, beginning from the bow and moving aft.[7] It was used solely to show how the waterline of the ship would change as subsequent compartments are allowed to flood to the waterline, and was used to show when water would have overtopped the transverse watertight bulkheads if carried to various heights.

Wilding's flooding by compartment work was investigated by naval architects Christopher Hackett and John Bedford in their landmark work of 1996.[8] For various flooding conditions, they were able to calculate the value of GM (the metacentric height) of the vessel as well as the amount of floodwater that would have entered the ship. During their progressive flooding of each compartment, the value of GM initially became larger than her intact condition GM (which they took as 2 ft 7½ in). This indicated that the transverse stability of the vessel was actually increasing somewhat with each progressive state of flooding. However, once their condition B6 was reached, where they flooded the fore-peak, holds 1, 2 and 3, and boiler rooms 6 and 5, they noticed that the transverse stability of the vessel had started to decrease as her GM began to get smaller. In that B6 condition, with about 31,000 tons of water taken in, the ship was shown to be well down by head with her stern raised out of the water (see Fig. 8).

Hackett and Bedford then went further by *partially* flooding boiler room 4, which was located just aft of boiler room 5, with 4,000 tons of flood water. What they then found was their calculated value of GM was reduced to only 9½ inches (GM = 0.8 ft), and the total displacement weight of the vessel would have reached 83,300 tons (35,000 tons of which was floodwater intake), a condition that would make the ship more tender.

If Edward Wilding, back in 1912, had also used a GM value close to 1 foot when *Titanic* was in a late stage of sinking, and if he estimated that the ship had taken in about 35,000 tons of sea water by that time, then we can replicate his calculation to find out how much correction would have taken place if 800 people were asked to move across the deck about 50 feet to help correct a list.

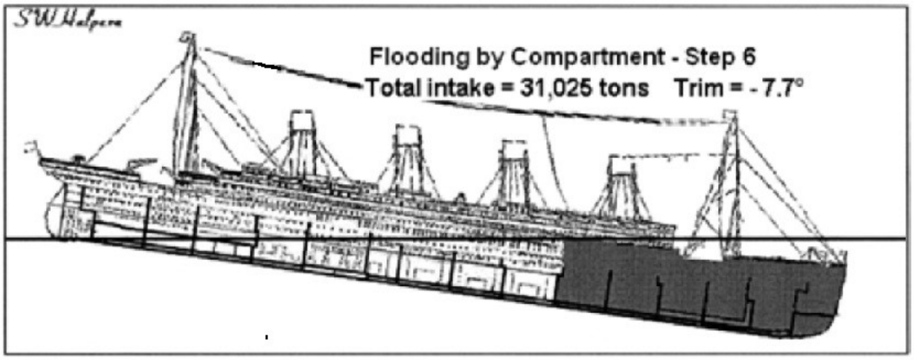

Fig. 8 – Profile view of *Titanic* with six compartments flooded (Wilding's Condition B6).

For our work we will take the GM to be 0.8 feet at this late stage of sinking, and we also assume that the vessel, which had weighed 48,300 tons just before the collision, had taken in some 35,000 tons of seawater by this time. It may also interest the reader to know that a value of GM close to about 1 foot is somewhat typical for an *Olympic* class vessel after completing a transatlantic voyage.[9]

In addition to all this, we will take the average weight of a person to be about 155 lbs, making the total weight of 800 people being asked to move equal to about 55 tons.

The *change* in the angle of list δθ *in degrees* produced by moving the weight (***w***) of a large group of people across the deck a distance (**d**) is given by the following expression (see Appendix–A):

$$\delta\theta \approx \mathbf{d} \times \boldsymbol{w} \times \mathbf{57.3°/(W \times GM)}$$

where in the above:

d = 50 ft (the distance that 800 people are asked to move across the deck),
w = 55 long-tons (the weight of 800 people obtained by using an average of 155 lbs/person, multiplied by 800 persons, and then dividing by 2240 lbs/long-ton),
W = 83,300 long-tons (the total weight of the vessel made up of 35,000 tons of water intake plus 48,300 tons of pre-collision displacement weight), and
GM = 0.8 ft (the metacentric height of the vessel at the time people were asked to move).

Putting these values into the equation above for the *change* in angle of list, we get:

$$\delta\theta \approx 50 \times 55 \times 57.3° / (83{,}300 \times 0.8) = 2.36° \quad \text{which rounds to } 2°$$

Recall, that when asked before the Wreck Commission, "Moving 800 people through 50 feet would right her 2 degrees?" Wilding's response was, "About 2 degrees."

Of course, we do not know exactly what assumptions Edward Wilding actually used when he did his calculation back in 1912. He only presented the result of what he did to the Wreck Commission. However, what we do know is that *Titanic* was carrying a list to port around 10° about half an hour before she foundered, likely the result of some asymmetrical flooding that took place over a period of time in her interrior. As the above analysis shows, moving a large number of people across the deck to try and correct that list would only have had a negligible effect at best, which is exactly what Wilding was trying to point out to the Commission. To the very end, *Titanic* never lost her transverse stability, something that tends to happen to most severely damaged vessels. Because she was able to maintain a relatively stable platform, 18 out of the 20 lifeboats that she carried were successfully launched from her davits.

Acknowledgment

I would like to thank Captain Charles Weeks, Prof. Emeritus in Marine Transportation – Maine Maritime Academy, and Mark Chirnside, noted maritime researcher and author, for taking the time to review this work, for sharing some archival data with me, and most of all, for their longtime friendship and support.

APPENDIX–A

Change in Angle of List When a Weight is Shifted Transversely Across a Deck

(A Technical Derivation)

Consider the somewhat exaggerated diagram in Fig. A-1 below that shows a vessel of **W** tons displacement at rest on a calm sea but listing a bit to one side at an angle θ after a group of passengers on deck, weighing a total of ***w*** tons, was asked to move a distance **d** from one side of the vessel to the other side. (For the purpose of analysis, we'll assume the vessel was initially on an even keel, and that the people on deck were initially distributed uniformly across the deck before a group of them was asked to move.) This example is similar to how marine engineers actually test a vessel's stability after a vessel is built.[10]

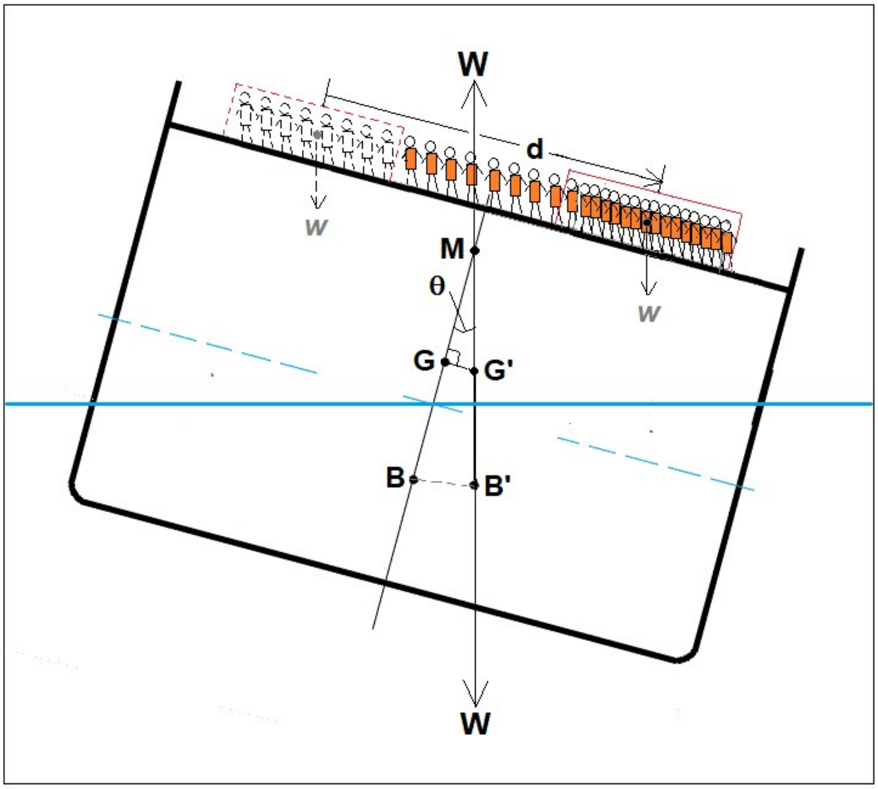

Fig. A-1 – Ship shown listing at an angle θ due to a shift of passengers.

For the vessel to remain in the position shown, the sum of all forces acting on the vessel must equal zero, and the sum of all turning moments acting on the vessel must also equal zero.

The total weight **W** of the loaded vessel, including all passengers, can be considered to be acting vertically *downward* from the vessel's center of gravity which is now located at point **G'** as shown. The shift of the center of gravity from **G** to **G'** was due to the shift in that large group of passengers that took place on the deck.

The second force acting of the vessel is the total force of buoyancy which acts vertically *upward* from the vessels center of buoyancy point which is now shown to be at point **B'**. The shift of that the center of buoyancy from point **B** to **B'** came about because of the change in the vessels under water hull form as the vessel listed to the side shown.[11]

The force of buoyancy must equal the total weight **W** of the loaded vessel (which includes everything on board) in order for the ship to remain afloat.[12] Furthermore, the force of buoyancy must act vertically upward through the shifted center of gravity point **G'** in order for the ship to remain stable in the position as shown. Thus, we find **B'** located directly under **G'**. In this position, there are no turning moments acting on the vessel to change the angle of list θ from what is shown in Fig. A-1.

So now how do we find out what the angle of list θ happens to be? To do that we can use some trigonometry from what is shown in Fig. A-1, and then apply some other principles and mathematics.

Consider the right triangle made up of the points M-G-G' shown in Fig. A-1. The length of $\mathbf{GG' = G'M \sin\theta}$ and the length of $\mathbf{GM = G'M \cos\theta}$.

Now take the ratio of **GG'** to **GM**, and we get:

$$\mathbf{GG'/GM = G'M \sin\theta / G'M \cos\theta = \sin\theta / \cos\theta = \tan\theta}$$

Or simply,

$$\mathbf{\tan\theta = GG'/GM} \qquad (1)$$

What we now need to find is how far did the center of gravity shift from **G** to **G'** as a result of moving that group of passengers weighing w tons across the deck by **d** feet.

The centre of gravity of a ship moves in the same direction as the centre of gravity of some mass within or on the ship that was moved.[13] Thus, if a mass of passengers are moved across a deck from port to starboard, the centre of gravity of the ship will also shift from port to starboard on a line parallel to the movement of the passengers. That is shown by the line from **G** to **G'** in Fig. A-1. However, the amount of that shift, the length **GG'**, is equal to the distance **d** that the group of passengers were moved, multiplied by the ratio of the weight w of those passengers to the weight **W** of the entire ship and its content. Thus,

$$\mathbf{GG' = d \times w/W} \qquad (2)$$

Now if we go back to the equation (1) we derived for $\tan\theta$, and substitute the above equation (2) for GG' into equation (1), we get:

$$\mathbf{\tan\theta = d \times w/(W \times GM)} \qquad (3)$$

For small values of θ we can expand $\tan\theta$ into the series $\tan\theta = \theta + \theta^3/3 + \ldots$ where θ is expressed in radians. And if we are concerned only for values of θ less than about 10° to 15°, we can ignore the second and higher order terms in the above expansion. Thus, $\tan\theta \approx \theta$ in radians, yielding:

$$\theta \approx \mathbf{d \times w/(W \times GM)} \quad \text{for small values of } \theta \text{ in } \textit{radians} \qquad (4)$$

Since there are 57.3° per radian, we get:

$$\theta \approx \mathbf{d}\times\boldsymbol{w}\times\mathbf{57.3°/(W\times GM)} \quad \text{for small values of } \theta \text{ in } \textit{degrees} \qquad (5)$$

Although we started out with the ship on an even keel before any weight was shifted, we could easily have started from some known condition of list which may have been caused by asymmetrical flooding or some internal weight that had shifted to one side to cause an imbalance. In that case, equation (2) above could have been written as:

$$\mathbf{GG' = d\times\boldsymbol{w}/W + k} \qquad (2')$$

where **k** is the shift in G resulting from the conditions that caused the ship to list to one side in the first place, and the term **d×*w*/W** is the amount that G would further shift if a group of passengers weighing ***w*** tons are then asked to cross the deck a distance **d**. (The distanced **d** can be taken as positive or negative.)

Using the above equation (2'), equation (3) now becomes:

$$\mathbf{\tan\theta = d\times\boldsymbol{w}/(W\times GM) + k/GM} \qquad (3')$$

and as long as θ remains small, we have:

$$\mathbf{\theta \approx d\times\boldsymbol{w}/(W\times GM) + k/GM} \qquad \text{in radians} \qquad (4')$$

Now let θ_0 = **k/GM**, the *initial list* of the vessel in radians before any large group of passengers were asked to move, and let δθ = **d×*w*/(W×GM)**, the *change in angle of list* (in radians) caused by the shifting of ***w*** tons of passengers a distance **d** feet across the deck. Then we see that the total angle of list *after* shifting a group of passengers across the deck is simply $\theta = \theta_0 + \delta\theta$, which is the list of the vessel before passengers were moved, plus the *change* in list angle after passengers were move.

Mathematically, **d** is taken as negative if people were told to move in a direction that would tend to *reduce* the angle of list, while it is taken as positive if they were told to move in a direction that would tend to *increase* the angle of list. Notice that if nobody was told to move at all, then **d**=0 resulting in δθ=0, and $\theta = \theta_0$ for that point in time.

To express these angles in degrees one simply multiplies the angles in radians above by 57.3° per radian. Therefore, the change in angle of list due to the shifting of a large group of passenger on deck a given distance becomes:

$$\delta\theta \approx \mathbf{d \times \boldsymbol{w} \times 57.3°/(W \times GM)} \qquad \text{valid for } \delta\theta \le 10° \qquad (5')$$

where **d** and **GM** are in feet, and ***w*** and **W** are in tons.

Endnotes

[1] Testimony of Robert Hichens, American Inquiry p. 451. See also my on-line article, "*Titanic*'s Initial List to Starboard," at: http://www.titanicology.com/Titanica/InitialListToStarboard.pdf.

[2] Testimony of William Ward, American Inquiry pp. 597-599.

[3] These forces include such things as wave and wind action, forces during a turn, shifting of weights or location of weights that are off-center.

[4] For small angles of heel in degrees, the righting arm GZ in feet is equal to GM in feet multiplied by the

angle of heel θ in degrees, divided by 57.3, or GZ = GM×θ/57.3. Since the righting moment is equal to the force of buoyancy times the righting arm (GZ), and since the force of buoyancy must equal the ship's displacement weight (W) in tons, the righting moment in foot-tons for small angles of heel is given by: GM×θ×W/57.3, where again GM is in feet, W is in tons, and θ is in degrees (for θ ≤ 10°).

[5] Samuel Halpern, "A Matter of Stability and Trim," http://www.titanicology.com/Titanica/Stability&Trim.pdf

[6] C. Hackett and J. G. Bedford, "The Sinking of S.S. *Titanic* – Investigated by Modern Techniques," 1996 RINA Transactions.

[7] Samuel Halpern, "Practically Unsinkable," shows Wilding's Flooding by Compartment sequence in an animated presentation along with explanatory text. This on-line presentation can be accessed here: http://www.titanicology.com/FloodingByCompartment.html.

[8] C. Hackett and J. G. Bedford, Section 3 – Recalculation of Data Presented to the Inquiry by Mr. E. Wilding of Harland & Wolff.

[9] Data for *Titanic*'s sister ship *Olympic* has shown that her metacentric height (GM) ranged from 2.73 ft when fully loaded at the start of a transatlantic voyage, to 1.17 ft at the completion of a voyage after the expenditure of fuel and other disposables. (Source: Mark Chirnside.)

[10] E. A. Stokoe, *Read's Naval Architecture for Engineers*, Thomas Reed Publications, Ch. 5 – Stability of Ships, 1993, "Inclining Experiment," pp. 78-81.

[11] The vessel being stable, with M above G, would list until B' finds itself directly under G'.

[12] The underwater volume of the hull form remains the same despite changing shape in order to keep the displacement of the vessel **W** (in tons of seawater) the same.

[13] E. A. Stokoe, Ch. 4 – Centre of Gravity.