THE SUTTON HOO SAXON SHIP – DEVELOPMENT AND ANALYSIS OF A COMPUTER HULL MODEL PRIOR TO FULL SCALE RECONSTRUCTION

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SUMMARY

This paper reviews recent research prior to a planned full-size reconstruction of the Saxon ship found at Sutton Hoo. The work included establishing the fundamental form of the ship by reviewing available historic information and data with consideration to possible distortion due to movement of ground and decay of timbers and likely units of measurements used based on measurement of Saxon buildings.

From this research a computer hull model was generated and hydrostatic and stability software used to assess the likely displacement, loading and stability characteristics. Performance under oar power was assessed with performance prediction software and a faired lines plan was generated from the computer model. The Woodbridge River Trust plan to commence construction of the full-size replica in 2017.

1. INTRODUCTION

In 1939 an ancient burial mound was excavated near Sutton Hoo in Suffolk and the remains of an Anglo Saxon ship uncovered. The ship was almost 27m (90ft) long, of wood clinker construction, propelled by up to 40 oarsmen and estimated to date to 625AD.

All of the original timber had decayed, but a well-preserved impression of the plank and frame surfaces was left in the ground and the iron rivets remained in place.

The excavation was cut short by the onset of war and little recorded data survives except for detailed photographs of the ship impression and a provisional lines plan produced by the Science Museum in 1939. In 1967 the site was re-excavated and further lines plans drawn, but by then the hull impression had considerable damage and the excavation team focused mainly on archeological aspects and construction.

The available records and data were reviewed so that an accurate computer model of the ship could be developed to look at the stability and performance characteristics and to provide a lines plan for the planed full-scale reconstruction.

2. HISTORIC DATA

The recorded information, drawings and measurement data available for study for this work included:

- Extracts from notes from the 1939 excavation written by C.W. Phillips and Commander Hutchison, in Volume 1 of the Sutton Hoo Ship Burial by Robert Bruce-Mitford [1].

- Detailed photographs taken in 1939, which provide a clear indication of the overall shape of the ship impression at that time.

- A plan prepared by the Science Museum in 1939 showing the hull lines, section shape at frames and rivet positions for planking. A full copy of the plan is held at the Ipswich Museum and the plan is also shown as Figure 135 in [1].

- Information and observations recorded by Robert Bruce-Mitford and Angela Care Evans following the 1967 re-excavation [1].

- Lines plans of the ship by Colin Mudie, one dated 1973 with hull sections at frame positions [1] and a second dated 1974, number 202.8

- A plan showing planking and rivet positions, including a body plan with hull sections at frames, (Figure 325 in [1]) described as an archaeological plan ‘based on 1939 photographic records and information gained by the 1967 re-excavation’.

- Measurement data of the rivet positions taken in the 1967 re-excavation and a permanent record of the 1967 shape taken via a glass fibre moulding taken to the British Museum

No detailed measurement data of the shape of the impression in the ground in 1939 was available, nor any offset tables for the lines plans listed above. Detailed measurement data was taken in the 1967 re-excavation but by this stage the impression had been badly damaged.

3. OBSERVATIONS ON DATA

3.1 1939 PHOTOGRAPHS

From the photos taken the first excavation in 1939, it can be seen that the overall shape was preserved extremely well with the rivets showing the lines of plank edges and some frames showing, although there were some areas of missing detail and local irregularities in shape. Figure 1 is one of several very clear photographs taken in 1939 by

Miss B. Wagstaff. By studying the photos the following points can be observed regarding the shape of the ship:

Extreme ends - It can be seen from the photographs that no detail was uncovered at the extreme ends of the hull in 1939. Figure 2, a photograph of bow taken by C. Phillips, shows this. The loss of the ends was probably due to the proximity to the ground surface and possible ploughing etc. Any drawings showing the bow or stern end extensions are not based on preserved evidence.

Mid-sections - Not much detail of the shape or position of frames can be seen in the middle third of the length of the boat, but considerable detail of frame shapes was preserved forward and aft of this middle section. Therefore, when interpreting the shape shown on any plans less emphasis was given to the middle sections than to the forward and aft thirds.

Bow and stern sections - The photographs in Figure 2 shows that the bow sections of the ship impression were flared out rather than the sharp and more vertical ends normally found on boats of this era, such as the Nydam boat [2]. The same was true at the stern.

The general consensus since the discovery of the Sutton Hoo ship is that this shape at the ends was probably caused by the planks springing away from the stem and stern posts. This could be explained if the sand and soil used to back-fill the cavity outside the hull when it was buried compacted downwards over time, reducing the support of the planks ends near the top of the mound. As the ends were near the ground surface and may have extended beyond the surface, decay of some timbers would have been faster here reducing support and allowing the planks to move.

Topsides - The spreading outwards of the bow and stern planking would have extended at least some way towards the middle of the boat, so throughout the length of the boat there may have been some slight outward movement of the top planks as the soil settled. There seems to be some evidence of this shown in the photos.

3.2 SCIENCE MUSEUM 1939 PLAN

A plan was drawn in 1939 by the Science Museum, part of which is shown in Figure 3. The plan, which was labelled as ‘provisional’, shows longitudinal lines and sections following fair curves without the local irregularities in shape that can be seen in the photos. It therefore seems reasonable to assume that when the plan was produced, fair curves were drawn as a best fit through the measurement data that was recorded at the time.

Although not stated, it is likely that measurements taken from both sides of the ship impression were averaged for this exercise, thus eliminating concerns over asymmetry, twist or angle of list, which are issues relating to the shape of the ship that were considered by the 1967 excavation team.

The process of creating fair hull lines by hand through a set of unfair points would have been fairly time consuming for the museum staff and they had little time available to do this in 1939 due to the impending war. Accordingly the museum plan’s lines are not considered to be a completely accurate record of the ship’s shape, particularly given that the ends of the ship are closer to the shape of the impression in the ground than to the shape that might have been expected for a ship of this type and construction.

3.3 1967 RE-EXCATVATION

In 1967 the Sutton Hoo ship mound was re-excavated to establish more information about the ship. Unfortunately the shape of the impression had by then been damaged by military training exercises on the land during the war, but is was still possible for the team to learn more about the ship, in particular relating to construction and areas of detail.

All rivets on the site were collected and preserved after their measurement positions had been recorded and eventually a full-scale glass-fibre casting was made of the impression. This was made in sections to allow transport to be stored at the British Museum. Figure 4 shows the casting assembled.

Although the casting has a boat shape, it is distorted locally and missing much of the top-sides due to the damage to the impression during the war, such that both Rupert Bruce-Mitford and Angela Care Evans stated that the re-excavation did not provide information on the overall shape of the boat that could improve on that recorded by the museum plan.

3.4 PLANS POST 1967

Several more provisional lines plans of the ship were drawn after the 1967 re-excavation, based on the data available from both excavations. At least two lines plans were prepared by the Colin Mudie design office and a further plan was produced illustrating the planking and some other construction detail.

The section lines shown in the Science museum plan were compared with the later lines plans and it could be seen that they all varied in shape. The 1973 Colin Mudie plan showed finer sections throughout the length of the boat than the Science Museum plan. The 1974 Mudie plan showed significantly fuller sections than the 1973 plan, closer to the shape shown in the Science Museum plan. Figure 5 shows a comparison of the 1973 Colin Mudie body plan and the museum plan – the fine lines are from the Colin Mudie plan.

The archaeological plan was somewhere in between the museum plan and 1973 plan, but the hull sections were not faired, so it would seem to be more of an illustration of the likely appearance with some constructional detail.

3.5 HALF-SIZE REPLICA

In 1993 a working half-size replica of the ship, named ‘Sae Wyfling’ was constructed by Edwin and Joyce Gifford. The lines plans drawn by Colin Mudie were used for the re-construction. The replica was both rowed and sailed, but for sailing the keel timber was extended in depth to improve lateral resistance.

4. DEVELOPMENT OF HULL LINES

4.1 INITIAL LINES BASED ON 1939 PLAN

In order for the 1939 Science Museum plan to be use as the reference shape for generating the initial lines of the ship on the computer, copies of the bow and stern body sections were scanned and printed at larger scale. Some missing detail at frames was added to the printed drawings by fairing curves between points shown clearly on the plan.

This enhanced plan was scanned again and the points representing the positions of the rivets used to join plank edges at each frame station were digitised using Maxsurf Modeller hull design software. The digitizing was done by first importing the scan of the museum body plan into Maxsurf as a background image then inserting ‘marker’ points over the plan section lines. These digitised marker points were then joined automatically by Maxsurf to re-create the museum body plan as a 2-D image that could be compared on-screen with the lines being generated for the computer model of the hull.

Maxsurf provides a number of options for automatically generating a 3-D hull model to fit a set of hull markers on defined stations. This approach is fine for assessing hydrostatics and stability but as the intention was to produce a fair lines plan the new hull model was generated manually from a small number of control points aiming to ensure fair curves that were a good fit to the marker data.

A computer model of a hull was developed this way and was a reasonably accurate fit to the marker data. If there had been complete confidence with the accuracy of the Science Museum plan then this initial computer hull model could have been presented as the lines plan for the boat. This however was not the case for reasons outlined above, so in order to develop hull lines that better represent the original ship a number of further adjustments were made to the shape.

4.2 ASSUMPTIONS FOR SHIP LINES PLAN

Finer ends - For reasons describe above, an assumption was made that the spoon-shape ends found in the ship impression and shown in the 1939 museum plan do not reflect the correct shape of the original ship. Accordingly the ends of the computer model were pulled in to create a shape that would be expected for planks attached to stem and stern posts as typically found on ships of similar age, construction and style, such as the Nydam boat [2].

Bow section fullness - When the forward sections of the museum plan were compared with the aft sections it could be seen that the forward sections were considerably fuller. There was no measurement data to check, but the difference in fullness could not be seen clearly in the photos.

As a rough check measurements were taken off some frame stations in the photos by measuring the camber of hull segments at these frames. This exercise did not show up much difference in curvature in the bow and stern, so it seems like that the extra fullness in the bow sections was unintentionally exaggerated in the museum plan, probably as a result of expediting the preliminary lines fairing process as discussed above. The bow section fullness was therefore reduced a little in the faired computer hull plan, although the forward sections remain slightly larger than aft sections.

Keel rocker - The computer hull model created to fit the markers from the museum plan had a small amount of keel rocker. This feature was retained throughout the fairing process as it has been suggested by Scandinavian experts that a boat of this type would have had some keel rocker and it is slightly easier to generate a fair hull (or to plank a hull) with a small degree of centreline rocker. This rocker line refers to the line of intersection of the garboard planks on the centreline rather than any additional projecting keel timber.

The lines generated by this fairing process show a smooth and fair overall shape with gently rounded section curves running into a bow and stern shape that may be considered typical for the ship type. Fig 6 shows the hull body section lines at frame stations with the hull markers shown as joined crosses, showing that the shape is quite close to the museum plan at most sections although a fairer set of lines with slightly less curvature in the bow sections.

5. LOAD AND STABILITY ANALYSIS

The faired computer hull model was examined using Maxsurf Stability software to get a feel for the likely displacement, loading and stability characteristics. Maxsurf allows the units to be switched from ft to metres at any time and for this exercise metric units were used even though the hull form was modelled around imperial measurements to reflect the likely original measurement units (see 7.1).

The lines plan, which is shown in Figure 7, represents the shape of ship with the section curves faired through the outside surface of the planks, excluding plank overlaps. This hull shape is a close approximation to the clinker hull shape and suitable for calculating hydrostatics, loading, stability and other performance aspects.

The displacement to the estimated design waterline shown on the Science museum plan, and referred to as the 'probable light load line', was found to be close to 16 tonnes. A rough weight estimate for the ship indicated that this might represent a realistic loading for the boat, as follow:

Area of planking including overlaps is approximately 110 sq. m. For specific gravity of oak of 0.72 and plank thickness of 2.5 cm (1 inch) the weight of oak planking is 1980 kg, say 2 tonnes. If frames, keel and floorboards are taken as 2 tonnes and a further 1 tonne for thwarts, tholes, gunwales, rivets and caulking then a rough estimate for the weight light-ship without ballast is 5 tons.

If the crew number is taken at 40 with average weight of 100kg each including oars and some kit, then the crew adds another 4 tons. If 10 passengers are carried this might add another ton, bringing the light load displacement to 10 tonnes.

If stores/cargo of 3 tonnes were carried and possibly 3 tonnes of ballast, then the total loaded displacement would be around 16 tonnes displacement which coincides with the estimated waterline on the Science museum plan. At this load the canoe body depth at mid section is approximately 2 ft and midship freeboard also 2ft, which might suggest that this is at the upper end of the load range rather than a 'light load' as stated on the museum plan.

The hydrostatics were run at a series of waterlines and the load range from 10 to 16 tons looked appropriate for the design. As an absolute limit, the displacement when loaded to the point that the gunwales were at the waterline was found to be 50 tonnes. Given the very light construction of ship it seems unlikely that it would have been used for heavy load carrying and this also raised the question as to whether or not any ballast would have been carried if it was solely powered by oars, as light weight would have been beneficial for performance.

Stability was checked for the range of load cases from 10 to 16 tonnes based on estimated vertical COG for the loads listed above, with no cargo load or ballast included for the 10 tonne load case. At each of these load cases the stability was substantial, such that ten persons, for example, could all move to one side of the boat at the same time with only a small angle of heel resulting.

A large angle stability assessment indicated that the hull could heel to 20 degrees at a 16 tonnes load before down-flooding, suggesting an ample reserve of stability for rowing but at the same time that it was unlikely that the boat was intended to be sailed at an angle of heel. So if any sail was used it would most likely have been for downwind sailing only. In general though, the characteristics of the form seem to be more in line with that of a large rowing vessel rather than a sailing boat.

6. HULL FORM AND PERFORMANCE

6.1 HULL FORM

The hull model developed is fairly symmetrical fore and aft although the forward sections are slightly wider and fuller than the stern sections, such that the longitudinal centre of buoyancy to the reference waterline is 2% of the waterline length forward of amidships. A longitudinal centre of buoyancy (LCB) forward of amidships is not unusual for historic ships, and given the potential advantage of greater buoyancy forward keeping the bows up in rough weather or for beaching in surf, it seems appropriate for the design.

The rounded hull sections are perhaps to be expected if the boat was designed for rowing as round sections reduce wetted surface area and hence drag, as well as achieving relatively low draught for any given load which would be helpful for operating in shallow water, such as restricted tidal areas.

The hull has a small amount of fore and aft rocker on the centreline which again is perhaps to be expected for a rowing craft, as it both reduces the wetted surface area in the ends and improves manoeuvrability in restricted areas. Some rocker would enable the bows of the boat to get closer to the shore edge when running up a beach to enable crew to disembark without getting too wet. Further, a small amount of keel rocker would enable the boat to be freed and turned more easily after grounding. So unless there was a need for deeper ends and keel depth - for lateral resistance for sailing - it seems reasonable that these features would be absent and the hull would have a small amount of rocker with shallow keel timber.

6.2 POWERING AND RESISTANCE

The prismatic coefficient for the model was approximately 0.6. This is towards the high end suggesting a hull capable of reaching a displacement speed of around 9 to 10 knots for a hull of this length and relatively low power from rowing.

The performance of the hull with respect to resistance, power and likely speed was further assessed for the final lines using both empirical and calculation methods in Maxsurf Resistance software. Power estimates for a range of speeds were calculated at 13 tonnes displacement by three empirical methods (Holtrop, Fung and upright resistance from the Delft III sailing VPP) and by applying slender body theory, which is applicable for the length to beam ratio and displacement of the ship. It can be seen from Figure 8, which shows the predicted power curves, that the methods compare quite closely over the expected range of speeds. The approximate predicted power is 10hp at 8 knots, 20hp at 9 knots and 30hp at 10 knots.

It is difficult to estimate the power delivered by a human with an oar, and also there is a question over the number of oarsmen, which may have been 28 or 40, depending on whether or not tholes for oars were originally fitted in the mid section of the ship but removed for the burial.

6.3 SEA-KEEPING AND STRUCTURAL INTEGRITY

As a further exercise the computer hull model was animated in waves of 1m height and 2m height. In waves of 1m it could be seen that the freeboard remained almost uniform as the bow and stern lifted the hull to the waveform. At 2m the ship appeared to be taking some water aboard at the ends, which could have been deflected by temporary decking. However, it seems unlikely that the ship would have operated in large waves as it's lightweight construction and low amidships freeboard may well have lead to structural issues.

As a further exercise the structural strength of the ship could be assessed to establish what the maximum load and wave height combinations would be whist still maintaining a good margin for structural integrity.

7. CONSTRUCTION

7.1 SCANTLINGS AND MEASUREMENTS

Measurements of the frame positions taken from the plans showed that the average frame spacing, ignoring irregular spacing at the ends of the boat, was very close to 3 feet (2.994 ft average).

This 3-foot frame spacing may be coincidental, but a review of measurements used in Saxon times for land buildings indicated that it was likely that there were two measurement systems in use at the time.

One was based on a 'rod', which was 15 German feet long with each German foot 13.2 inches long, so the German rod was 16.5 modern feet long. The other was based on Roman units where a 'rod' was 15 feet long with each foot 12 inches long, these feet and inches being the same size as modern imperial units.

It therefore seems a reasonable assumption that the Roman/current imperial measurement system was used for the Sutton Hoo ship, particularly when further noting that the overall distance between the end-most frames is 75 feet or 5 'rods'.

Also, that the average planking thickness is 1 inch based on measurements taken from plank scarf join rivets. And while it could be coincidental, it was noted that the average width of the hull planks in the mid sections is approximately 1 ft - see 7.2 below.

If this measurement system assumption is correct, then it would suggest that there has been no significant expansion or contraction of the ground over the 75 ft length between the end frames, and that the overall dimensions of the impression may be considered very accurate, perhaps more so than the dimensions of preserved historic wooden ships where timber distortion and shrinkage can lead to considerable speculation over the original ship dimensions and shape, as is the case for the Nydam ship, as shown in Figure 10.

7.2 PLANKING AND FRAMING

The plank runs as recorded by the rivet positions shown on the Science Museum plan were represented on the computer by marker positions. There were some discrepancies found in the shape of the longitudinal lines passing through these points, which represent the plank overlap paths, particularly in the mid portion of the boat, which is perhaps to be expected due to the lack of detail uncovered in the mid section.

The plank widths (from plank edge rivet to rivet) were recorded at longitudinal positions during the re-excavation and although this information is also mostly missing for the mid portion of the boat it does give a good idea of the average plank width, which is around 1 ft, excluding plank taper in the boat ends. This is based on 10.5 inch average distance between the edge rivets plus 1.5 inch plank overlap.

As a further check on plank width the girth of the midship frame section of the computer hull model was measured and it was found that the correct girth would be achieved by 9 clinker planks each of 1ft width with overlaps around 1.3 inches. This was based on a half-girth measurement of 8.5 ft less a small amount for the keel timber width and a slightly wider sheer plank.

The plank timber is thought to be oak. The planking would have originally been made by splitting trees and trimming the planks with adze or axe [3]. The intention is to attempt to produce planks in the same way for the reconstruction of the ship.

The lines plan derived from the computer model shows a frame spacing of 3ft except for the end frames beyond the drawn waterline, so that the frame positions will coincide closely with the original frame positions. A nominal design waterline was drawn with a draught of 2ft which gives a waterline length of 60ft with the forward perpendicular (FP) at Frame 3.

8. CONCLUSIONS

Despite the complete absence of any of the original timbers, it can be concluded that the impression in the ground provided a remarkably good record of the ship's shape, perhaps even more reliable than historic ships that are found intact but subject to indeterminate distortion and shrinkage of the timbers. Such was the preservation of the layer between the timbers and surrounding sand and soil, and the 'map' of rivets, that it was also possible to establish considerable construction detail too.

Taking into consideration the available recorded data on the shape of the impression and subsequent analysis, a fair computer model of the hull has been generated. In addition to providing a lines plan for the planned reconstruction of the ship this model provided useful information on stability and likely performance.

The Woodbridge Trust plans to start construction of the full-scale replica in 2007 at a special site in Woodbridge, where the boat will eventually be based for public viewing.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

1. BRUCE-MITFORD, R., Volume 1 of The Sutton Hoo Ship Burial, British Museum, 1975

2. ABEGG-WIGG, A., 'Das Nydamboot', 2014

3. CONSTANTINE, P., 'Anglo-Saxon Craft Construction', 2015

11. AUTHORS BIOGRAPHY

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Figure 1: The ship trench in 1939, photograph by Miss B. Wagstaff

Figure 2: Bow sections of the ship impression, photograph by C. Philips

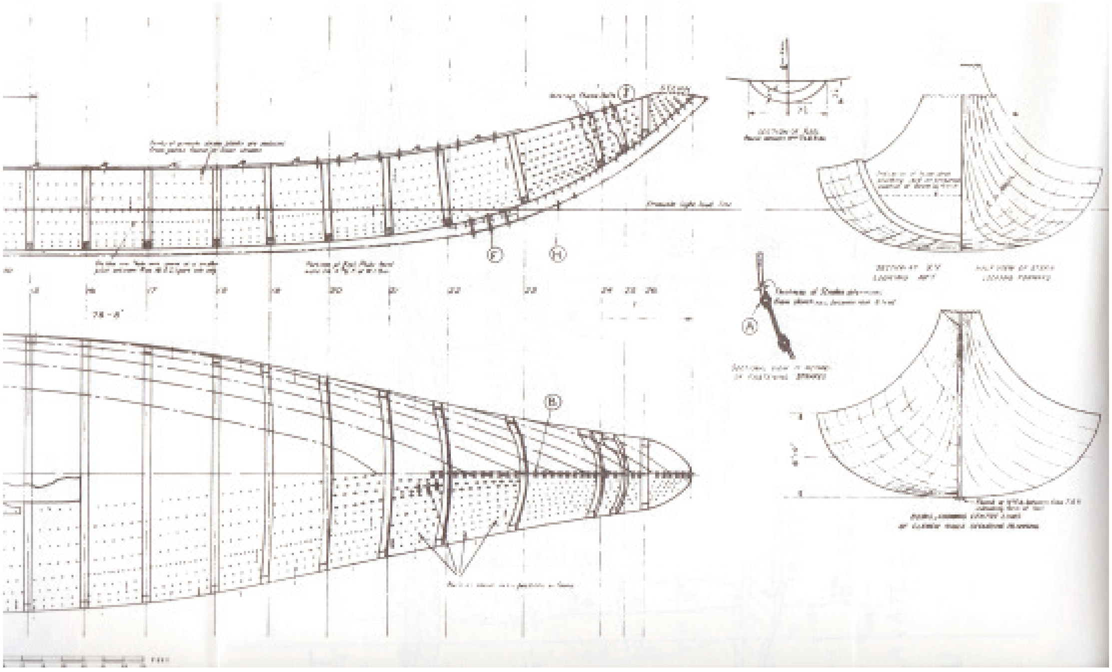

Figure 3: 1939 Science Museum plan

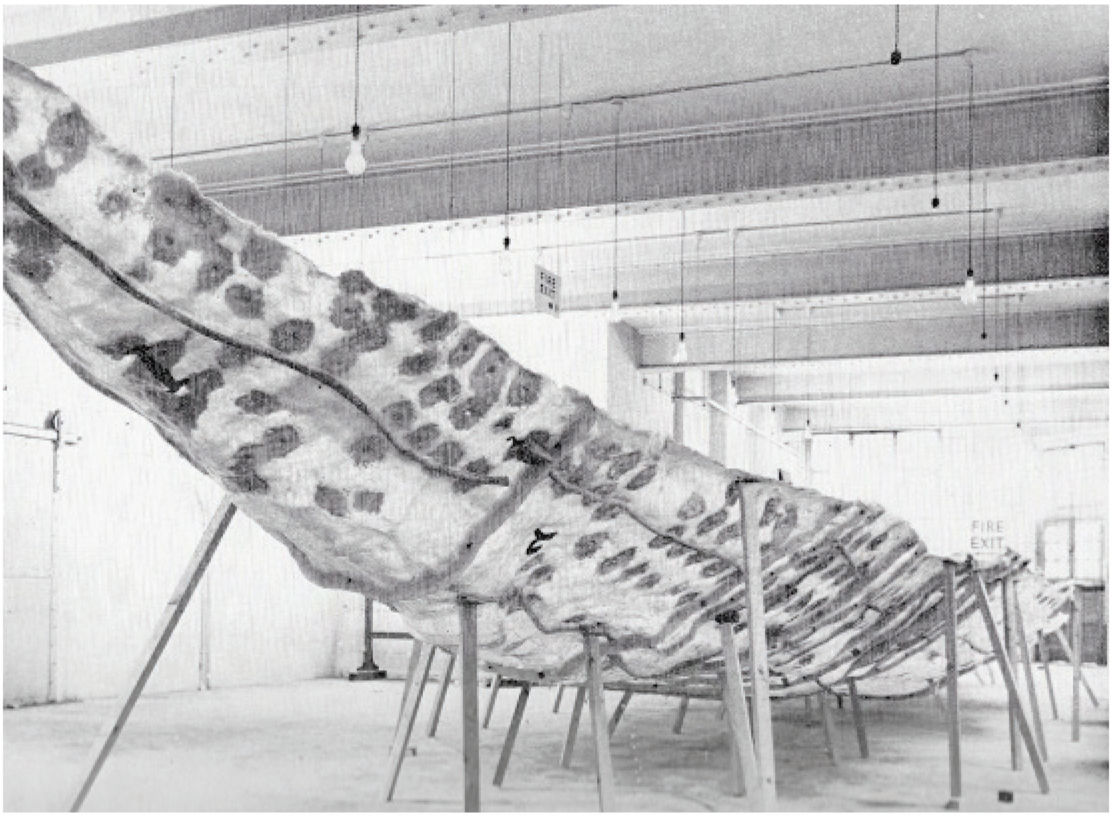

Figure 4: Casting of the 1967 ship trench, photograph by BBC

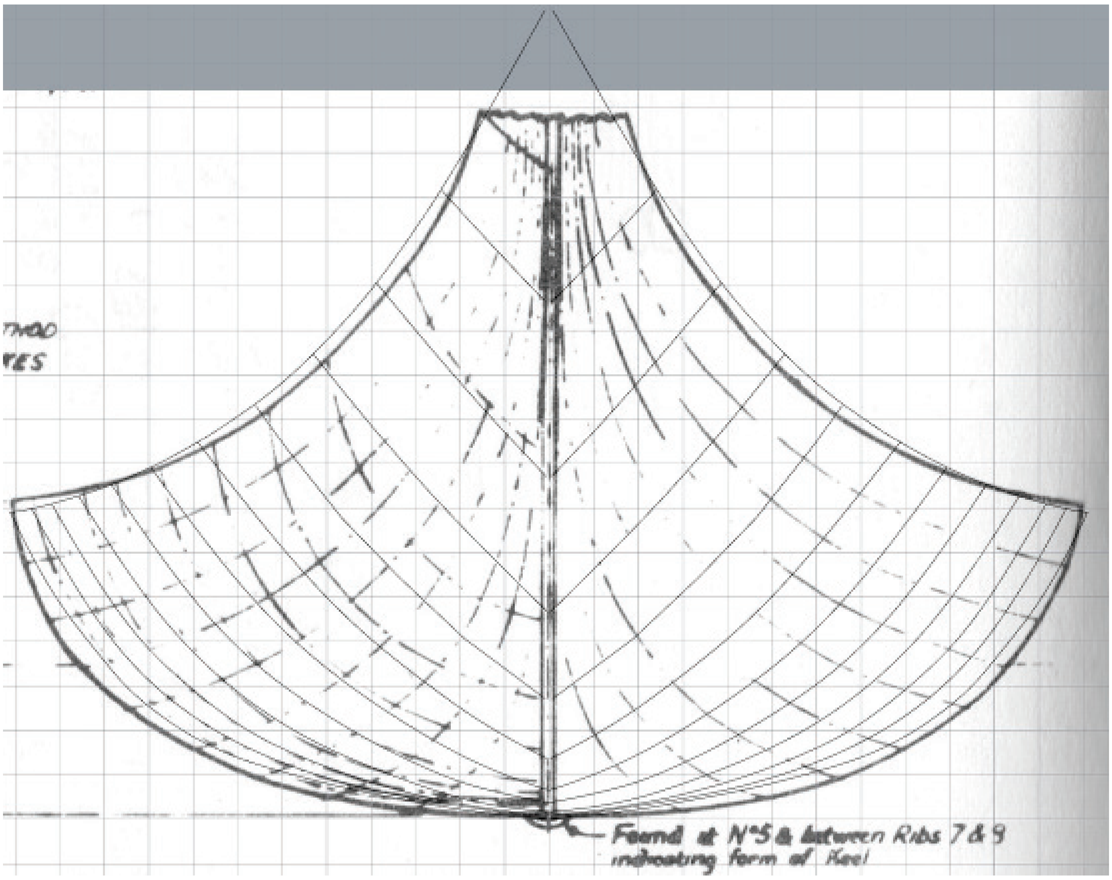

Figure 5: Comparison of body plan by Science Museum and Colin Mudie (1973)

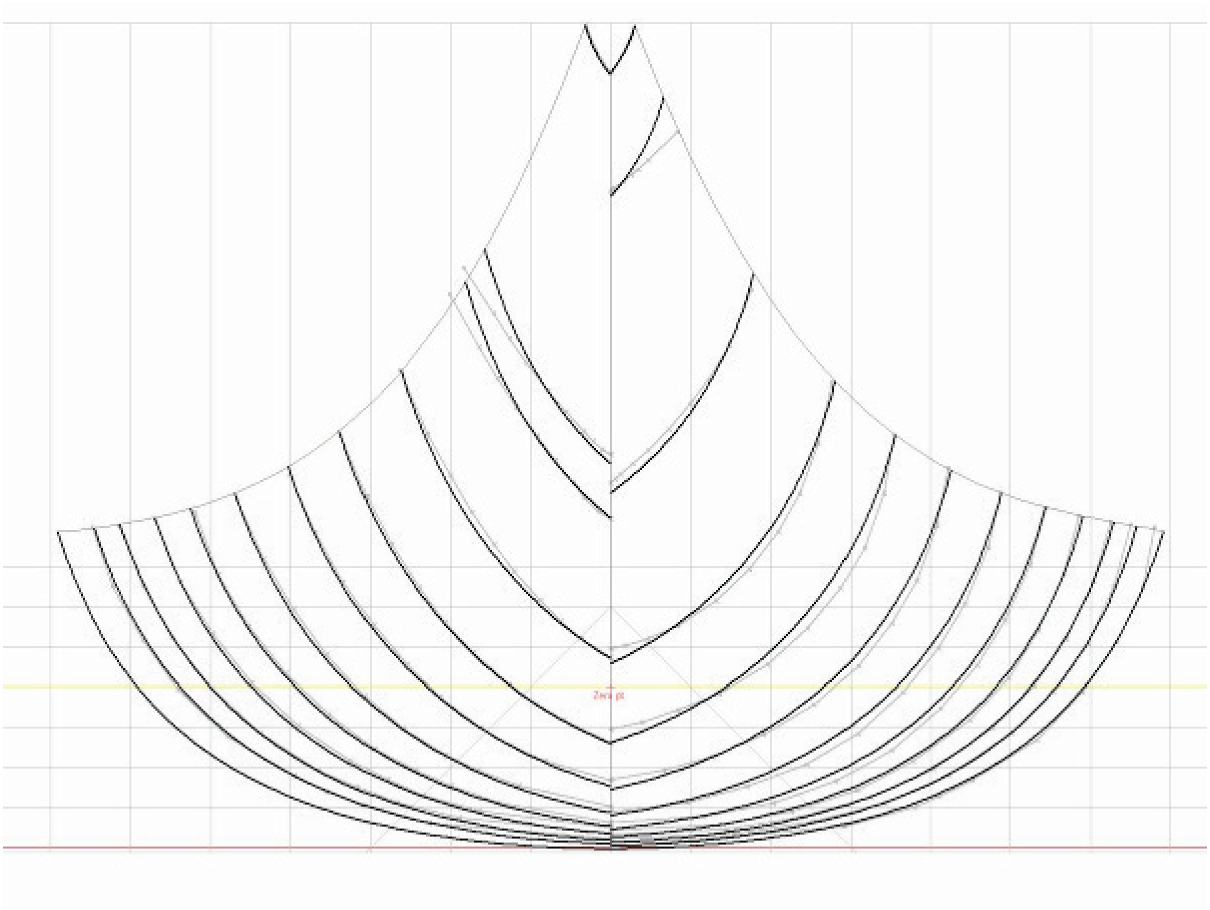

Figure 6: Computer body plan lines compared to Science Museum lines (through makers)

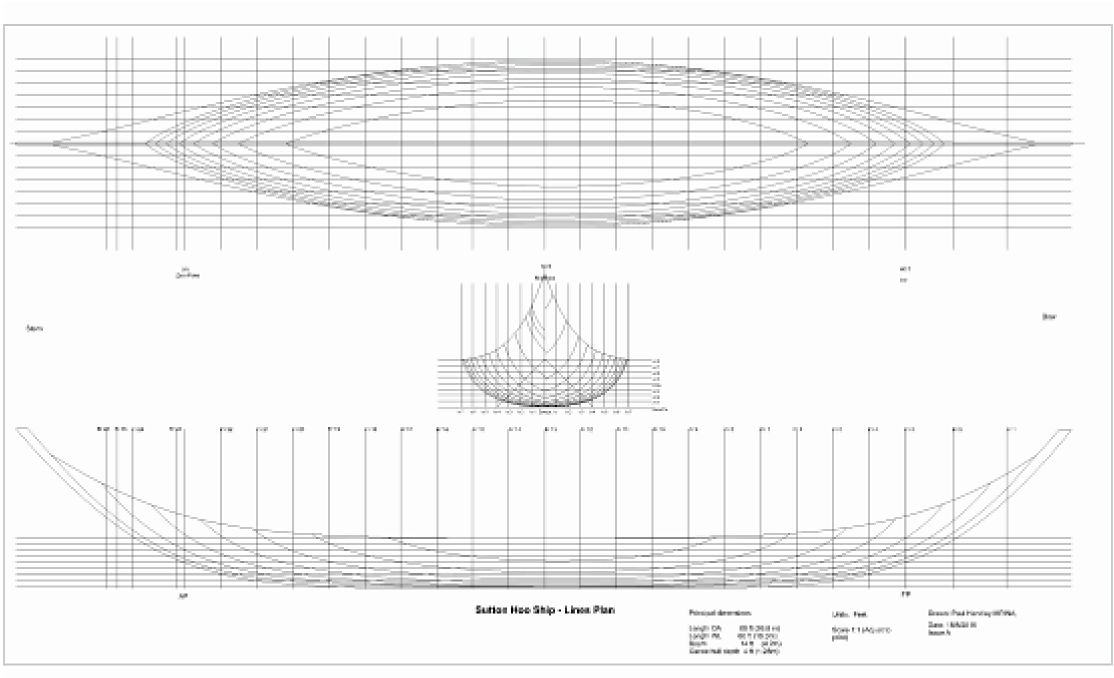

Figure 7: Lines plan from computer model

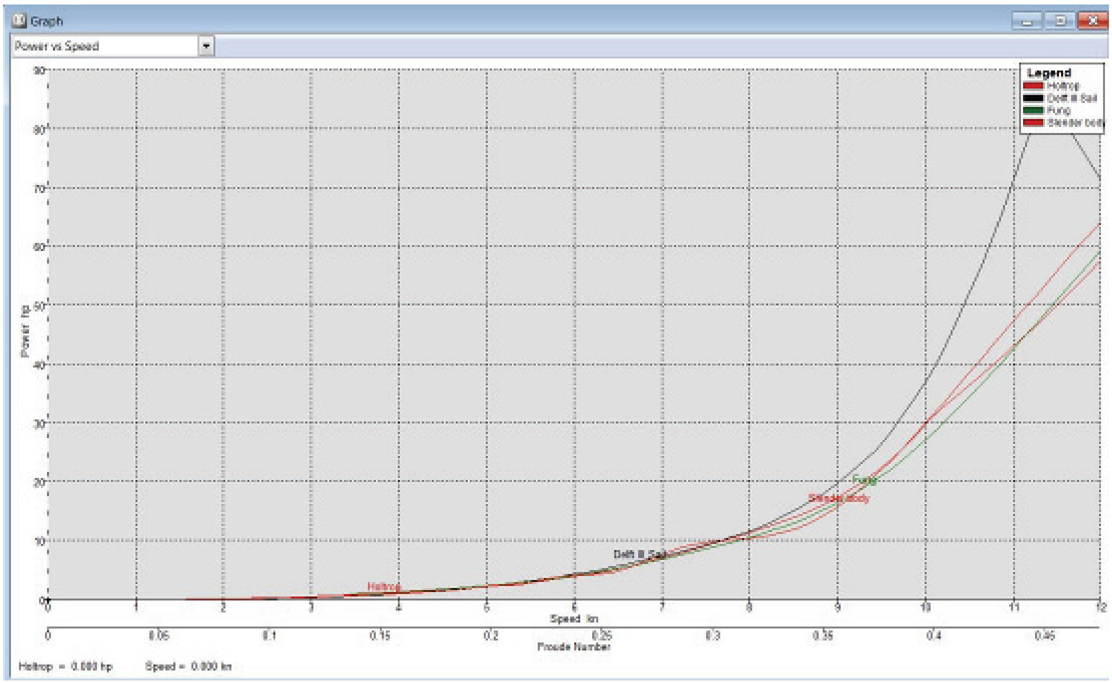

Figure 8: Predicted power curves for Saxon ship

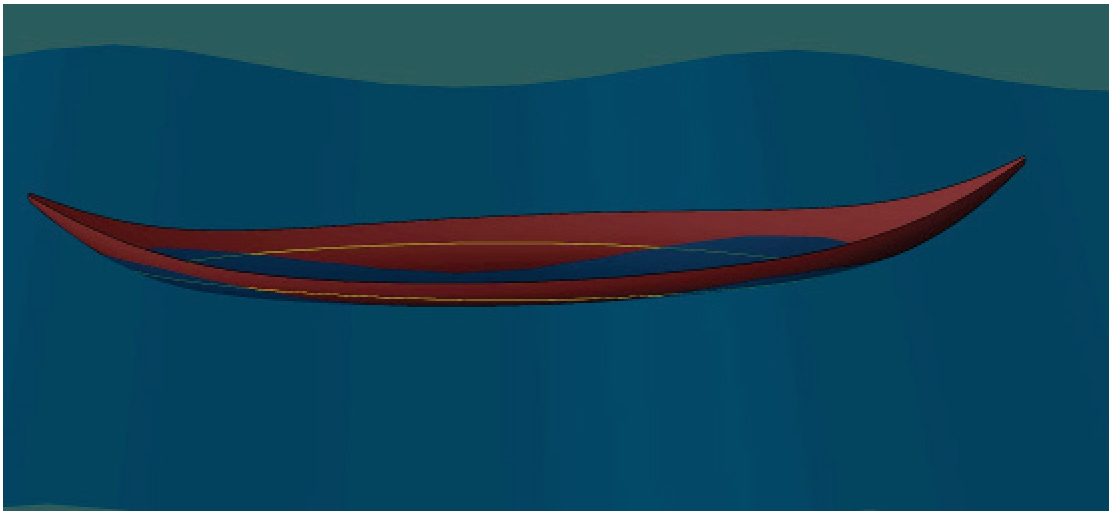

Figure 9: Ship in 1m waves

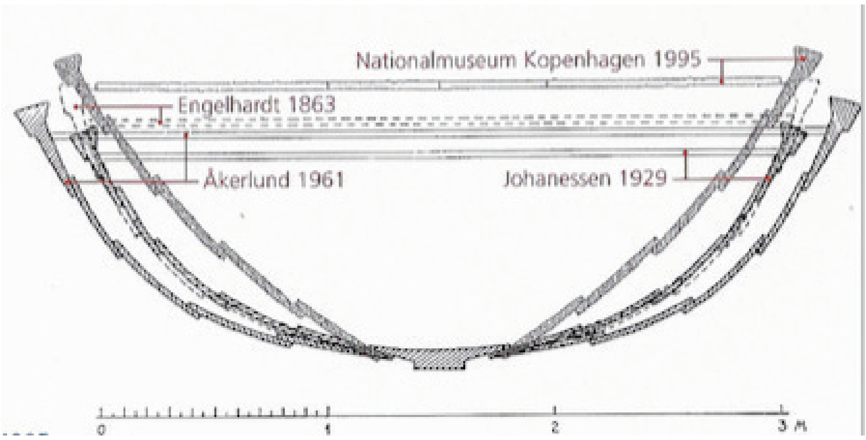

Figure 10: Interpretations of shape of Nydam boat