Journal of Hellenic Studies cxvi (1996) pp 88-107

THE CONSTRUCTION OF XERXES' BRIDGE OVER THE HELLESPONT*

THE bridging of the Hellespont by Xerxes was a unique achievement. How was it done? The Chorus of Elders in Aeschylus' *Persians* expressed their wonder at 'the flax-bound raft', and Herodotus described the construction of the two bridges, each with warships as pontoons, with cables well over a kilometre long, and with a roadway capable of carrying a huge army. Classical scholars have generally found these accounts inadequate and even inexplicable, especially in regard to the relationship between the pontoons and the cables. The Hellespont has strong currents which vary in their direction, turbulent and often stormy waters, and exposure to violent winds, blowing sometimes from the Black Sea and sometimes from the Mediterranean. How were the warships moored in order to face the currents and withstand the gales? Did the warships form a continuous platform, or was each ship free to move in response to weather conditions? What was the function of the enormous cables? How and where were they made? Did they bind the pontoons together? Did they carry the roadway? How were they fixed at the landward ends? This article attempts an answer to these questions through the collaboration of a classical scholar and a mechanical engineer.

In 1988 I expressed my conclusions on this subject in the limited space which was available in *The Cambridge Ancient History* iv 527-32. They were based on the description by Herodotus, which I, unlike Macan, found to be neither 'inadequate' nor 'unintelligible', and on an amateurish knowledge of bridge-structures which I had acquired for purposes of demolition in time of war. A justification of some of those conclusions is attempted here; others are superseded. Moreover, while teaching in the University of Washington in 1993, I had the good fortune to discuss the technical problems with a mature student of history, Lawrence J. Roseman, who had retired as the Program Manager of the AWACS Airplane 'Radome' of the Boeing Company, whose engineering expertise is in stress analysis. As he had further new ideas, we decided to undertake a joint article. I have written 'Testimonia' and 'Commentary', which deal with the ancient evidence, and Mr. Roseman has written the section 'Feasibility of the Reconstruction'. Finally we give a 'Summary of the Main Arguments', to which we both subscribe.

N.G.L. HAMMOND

A. TESTIMONIA IN TRANSLATION

1. Herodotus vii 25.1. For 'the bridges' over Strymon 'Xerxes was preparing also cables of papyrus and white-flax, issuing his orders to Phoenicians and Egyptians.'

2. Herodotus vii 33. 'Between Sestus city and Madytus there is a rugged headland coming down to the sea opposite Abydus' (*cf.* ix 120.4).

* The following abbreviations are used:

Burn	A.R. Burn, *Persia and the Greeks* (London 1962)
CAH	*The Cambridge Ancient History* iv (Cambridge 1988) eds. J. Boardman, N.G.L. Hammond, D.M. Lewis and M. Ostwald
Casson	Lionel Casson, *Ships and seamanship in the ancient world* (Princeton 1971)
Chapman	Charles F. Chapman, *Piloting, seamanship and small boat handling* (New York 1958)
H. and W.	W.W. How and J. Wells, *A commentary on Herodotus* i and ii (Oxford 1912)
Kutz	Myer Kutz ed., *Mechanical engineer's handbook* (New York 1986)
LSJ	H.G. Liddell, R. Scott and H.S. Jones, *A Greek-English lexicon* (Oxford 1953)
Macan	R. Macan, *Herodotus vii-ix* (London 1908)
Maurice	F. Maurice, 'The size of the army of Xerxes in the invasion of Greece, 480 BC', *JHS* i (1930) 210-35
Myres	J.L. Myres, *Herodotus: father of history* (Oxford 1953)

3. Herodotus vii 34. 'Starting from Abydus the appointed persons were bridging, Phoenicians the bridge of white-flax and Egyptians that of papyrus. From Abydus to the land opposite is seven stades. But a great storm chopped it all up and broke it apart.'

4. Herodotus vii 36.1. 'They bridged as follows. Placing penteconters and triremes together, 360 under the bridge facing the Black Sea and 314 under the other; and in the Black Sea one (they were) at an angle and in the Hellespont one (they were) according to the current,[1] in order that he might relieve[2] the tension of the cables.'

5. Herodotus vii 36.2. 'After placing them together, they let down very long anchors, those facing the Black Sea in the one (bridge) because of the winds that blow out from within (that sea), and those in the other (bridge) facing the evening and the Aegean because of the west wind and the south wind. And they left a narrow space as a way through the penteconters and (? the triremes at three places)[3], in order that anyone wishing to sail in light craft both to and from the Black Sea could do so.'[4]

6. Herodotus vii 36.3. 'After doing that, they began to extend the cables from the land [*cf.* Hdt. iv 72.4 χαλινοὺς...κατατείνουσι ἐς τὸ πρόσθε, and see LSJ s.v. κατατείνω i 4 and 6] twisting the cables with wooden donkeys (i.e. capstans), no longer employing the two types separately but for each bridge dividing them so as to be two of white-flax and four of papyrus. Thickness and fine quality were the same, but the flax ones, of which a cubit weighed a talent, were heavier relatively.'

7. Herodotus vii 36.4-5. 'When the strait was bridged, they sawed up tree-trunks, and making them equal to the width of the raft they arranged them in order on top of the taut cables, and after placing them there in order they joined them at the top thereafter. That done, they piled brushwood, and placing the brushwood in order they piled up earth, and beating the earth down firmly they drew a palisade alongside, on this side and on that, to prevent the draught-animals looking over at the sea and being frightened.'

8. Herodotus viii 117. 'They did not find the rafts still tight-stretched but broken apart by a storm.'

Herodotus ix 114. 'They found the bridges broken apart, which they expected to find tight-stretched.'

9. Herodotus ix 115. 'Oeobazus a Persian had brought the cables from the bridges' (to Sestus).

Herodotus ix 121. 'They sailed off to Greece, taking the cables of the bridges . . . to dedicate at the shrines.'

[1] The words τοῦ μὲν Πόντου and τοῦ δὲ 'Ελλησπόντου resume τὴν πρὸς τοῦ Εὐξείνου Πόντου and τὴν ἑτέρην. They are not dependent on ἐπικαρσίας and on κατὰ ῥόον, as Grote, Rawlinson and Macan suggested (H. and W. ii 142); for that interpretation would reqire a different order of words and there is no sense in the proposed translation 'at right angles to the Black Sea.' See Myres 222, who translated as I do. D. Hill, *A history of engineering in classical antiquity* (London 1984) 65 followed Rawlinson.

[2] The subject of ἀνακωχεύῃ is uncertain. H. and W. ii 143 supposed it was 'the bridge (i.e. here the moored ships)', but they had just said that 'Herodotus regarded the cables with the roadway as the true bridge.' I suppose that Herodotus had Xerxes' engineer in mind as the personal subject.

[3] See the *apparatus criticus* of the Oxford Classical text for suggested emendations. Since τριηρέωνand τριχοῦ begin with the same three letters, one word could easily be omitted by a scribe. There are no paleographical grounds for emending τριχοῦ to διχοῦ (H. and W. *ad loc.*)

[4] The importance of providing more than one bridge, for instance at the Hellespont, was appreciated by Maurice 224-5. But H. and W. ii 169 wrote of 'the bridge' despite the plural word at vii 25.1 and vii 114-5.

10. Aeschylus, *Persae* 68-73. 'The royal army . . . crossed the strait on a flax-bound raft, casting a much-bolted way as a yoke upon the neck of the sea.' 104 'trusting in light-made ropes and people-carrying devices.' 130-1 'crossing the sea-washed headland which yokes both sides in common of the two continents.' 722 'he yoked the Hellespont with devices.' 736 'he was glad to reach the bridge which yokes two continents.' 745 'he hoped to check the flow of the sacred Hellespont like a slave, with shackles, the Bosporus a god's river, and he devised a new form of crossing, and throwing hammer-wrought fetters around it he created a great pathway for a great army.'

11. Arrian, *Anabasis* v 7.2. 'If the narrows (of the Indus) were bridged with vessels, I cannot decide whether it was the case that, as Herodotus says of the bridging of the Hellespont, the warships being set together with ropes and lying at anchor in a row were sufficient to constitute the bridging.'

B. Commentary on the Testimonia

1. The first mention of cables in bridges was during the preparations for the invasion by Xerxes. For the bridge which was built for Darius over the Bosporus *c.* 513 BC was described as a 'raft' both by its architect, Mandrocles of Samos, and by Herodotus in his text (iv 88.1-2; 97.1; 98.3); and it seems that part of it was removed for the passage of Darius' flagship (iv 85.1). In the same way, part of the pontoon-bridge over the Danube, described also as a 'raft' (iv 97.1 and 98.3 σχεδίη), was removed and later replaced (iv 139.1 and 141). If this had been a cabled bridge, the cables would have been left in position.

Herodotus was interested in the material from which the cables for Xerxes' bridges over the Strymon were made. Papyrus, grown in Egypt, was probably well-known to the Greeks. But 'white-flax' (λευκόλινον), later called λευκέα 'from Spain' (Athenaeus, 206 F) and evidently brought from there by the Phoenicians, was a form of esparto-grass, less well known. At least two bridges were built over the Strymon (not one, as Myres 219 and 228 wrote), in order not to have a bottleneck for Xerxes' huge forces. One was at Nine Ways (vii 114.1). Another was presumably at the mouth of the Strymon, then near Eion, where Xerxes had laid a dump of supplies (vii 25.2 'Ηιόνα τὴν ἐπὶ Στρυμόνι; *cf.* vii 113.1). The terrible winds which blew 'from the Strymon river' were famous (Aesch. *Ag.* 192 and Arist. *Vent.* 973 b 17, cited by H. and W. ii 274).

2. The headland (ἀκτή) was 'rugged' because it was rocky; and it was with reference to this headland that Strabo wrote of Xerxes' landing-place on the European side as the 'Apobathra' at the 'Sestian promontory' (591 and 331 fr. 55 'Αποβάθρα καθ' ὃν ἐζεύγνυτο ἡ σχεδία). The starting-place for this bridge was not at Abydus city, which lay to the south of the strait, but within its territory.[5] It was undoubtedly somewhere on the low-lying coast east of Nagara Burnu. We are not told where the other bridge started and ended. Myres was probably correct in having it start at Nagara Point and end at the 'firm beach' west of the 'gravelly delta' of the stream on the European side. Stanley Casson[6] provided views of the very low-lying coast at and east of Nagara Burnu in his figs. 78 and 79. He noted from personal observation that 'the one long stretch of route along the European shore fit for lateral traffic and capable of being

[5] Maurice, taking Abydus to mean 'Abydus city', carried the bridges from the city over to the coast not of Sestus but of Madytus, reckoned the length of each bridge there as 4,220 yards, and exposed both bridges to changing currents (217). For the site of Abydus city, see J.M. Cook, *The Troad* (Oxford 1973) 56.

[6] *Macedonia, Thrace and Illyria* (Oxford 1926).

made fit for wheeled transport' was 'between Sestus and Gallipoli town' (214; *cf.* x [7]). This, he maintained, was the route used by Xerxes' army.[7]

3. Herodotus here stressed the novel feature of the bridges, namely the cables of white-flax and of papyrus; and it was with reference, it seems, to the cables that he added the distance of seven stades (1,295 m.),[8] as at iv 85.4. They were indeed very long cables. The width of the strait from Sestus to Abydus was given as 'not more than eight stades' (1,480 m.) by Xenophon, who knew the area well (*Hell.* iv 8.5). Strabo (125 and 591) and Pliny (*NH* iv 75) agreed with Herodotus. It seems best to accept Xenophon's figure and round it up to 1,500 m.

The distance today across the strait is some two kilometres. Since this crossing was much used throughout antiquity, and since the measurement was needed in 481 BC for instance, for making the cables, it is sensible to accept the ancient traditions. How and Wells wrote 'the difference may be explained by the washing away of the coasts by the strong currents' (ii 140). This would apply especially to the south coast, which is 'fringed, almost throughout its length, by a shallow bank which extends over half a mile offshore in some places' (*Black Sea Pilot[10]* 83). Another factor is the lower level of the Aegean by some five feet in antiquity.[9] Neither can a change in the level of the land since antiquity be excluded.

The destruction of the two bridges through 'a violent storm', such as is common in these waters (*Black Sea Pilot[10]* 21 and 84), was graphically described: 'a great storm chopped it all up and broke it apart' (χειμὼν μέγας συνέκοψέ τε ἐκεῖνα πάντα καὶ διέλυσε). Wind and wave evidently tore the warships of the pontoons from their moorings and snapped all the cables, of which some parts would be swept away waterlogged. For the emphatic 'all' included both ships and cables.

Herodotus completed his description of the first bridging and its after-effects, ending with the decapitation of the overseers. He begins the new bridging with the appointment of other directors (vii 36.1). There is no indication that any cables from the first bridging were re-used.

4. We may note that in the Persian fleet the triremes were decked (Plut. *Them.* xiv 2), and thus could carry more than thirty marines or other passengers (Hdt. vii 184.2; viii 118.2 *katastroma* in the singular). Since the Persian tactic was to ram and then to board an enemy vessel, the 'Ionian' triremes in the Persian fleet carried numerous marines (Hdt. viii 90.2, Samothracian javelin-men). The same was true of the penteconters; for they carried thirty men in addition to their fifty oarsmen (Hdt. vii 184. 3). The decks on the ships of the bridges made the roadway on them more stable and spread the load on each ship.

Herodotus described the stages of the construction one by one. In the first stage the warships (which were to become the pontoons) were placed in two lines across the channel, the eastern line being longer than the western line. The warships facing the Black Sea were at a right angle to the center line of the bridge. Those facing the Hellespont (τοῦ δὲ Ἑλλησπόντου being contrasted with τοῦ μὲν Πόντου) were 'according to the current', i.e., not at a precise right angle.[10]

The reasons for these different alignments are to be found in the local conditions. The warships of the eastern bridge were at a right angle to the center line of the bridge, because they

[7] Maurice, who seems to have been unaware of Stanley Casson's work, proposed an inland route on his map (218). The huge army certainly used more than one route (*pace* Casson and Maurice) in the Chersonese as in Thrace (see *CAH* iv 537-9), and not just the one route even for a 'double column, one of troops and one of transport' (Maurice 224).

[8] Maurice's location for the bridges made the distance to the other coast 4,220 yards, which is vastly more than seven stades (217). In making the stade 185 m. I follow P.A. Brunt, *Anabasis Alexandri* i (Harvard 1976) 488.

[9] For this calculation see Hammond's summary in *Ancient World* xxv (1994) 23-4.

[10] See (n. 1) above.

were facing 'the main current' which 'fills the whole width of the strait between Nagara Burnu and Bigali Kalesi (Fort)' (*Black Sea Pilot*[10] 25). Polybius commented on 'the swiftness and the violence of the current in the strait' (xvi 29.14). On the other hand, 'at a bend' (in the channel) 'the main current sets strongly towards the convex side', and this causes 'an eddy with a counter-current flowing northward along the shore' (*Black Sea Pilot*[10] 22). These antithetical currents could be exploited by merchant ships in making the crossing (Strabo 591).[11] It is evident that the warships of the western bridge were at somewhat different angles in relation to the center line of the bridge in order to face the current bow on, in each case. The purpose of these alignments was to offer the least possible resistance to the flow of water and thus to put the least possible strain on the cables of the anchors (which Herodotus described next). The reference in his word 'cables' (ὅπλα) here is not to the kilometre-and-a-half cables, which were affected only very remotely, but to the anchor-cables.

5. The unusually long anchors were evidently designed to hold fast against both the wind and the current which may reach a speed of three knots in the narrows and, under abnormal conditions, as much as five knots (*Black Sea Pilot*[10] 23). 'The holding ground is good' off the south shore (*ibid.* 83). I take it that the warships, when in position as pontoons, were anchored bow and stern.

'The narrow space' was to be used by 'light craft' (πλοίοισι λεπτοῖσι; *cf.* viii 137.2 τὰ λεπτὰ τῶν προβάτων), presumably low barges either under oar or under tow. The narrow space lay presumably between triremes, in order to give more headroom. The text, reading τριχοῦ or τριχῇ, can best be emended to τριηρέων τριχοῦ which would mean that there were three such spaces at places where the best use could be made of the main current and of the counter-currents.[12]

6. The translation which I have given described the twisting of the strands to make a cable. This was done with capstans, as they proceeded 'from the land' and reached the other coast. For the technique of cable-making see C 1. Capstans or 'donkeys' (as in the modern term 'donkey engine') had long been in use (probably since the seventh century; see J.J. Coulton in *JHS* xciv [1974] 12. n. 69).

The usual translation of this passage is that of G. Rawlinson. 'When all this was done, they made the cables taut from the shore by the help of wooden capstans'. Here he omitted the important word 'twisting' (στρεβλοῦντες, the tense being contemporary with κατέτεινον). Once the cables were made, 'tightening and twisting' them would have damaged them beyond repair. See C 1. How were the ends of the cables secured on land? Herodotus did not say. However, in *CAH* iv 531 I made what was, I think, an original suggestion, that the capstans and the cables were attached to land-piers. 'These piers', I wrote, 'had to take an immense strain. I imagine that narrow shafts (as in ancient mining) were sunk in the rock and that large timbers, reinforced perhaps with metal rods, were placed in the shafts, so that their tops formed the land-anchors of the cables. The cable-ends were set at about the same level as the roadway which they were intended when taut to carry.' The cables were continuous from shore to shore, each being some 1,500 m. long.[13] The slack in a cable was taken up when it was attached to its second land-pier. A method of doing so is suggested in C 5. Thereafter the cable was described as 'taut'.

[11] See H. and W. ii 143, whereas Maurice did not consider the currents in his siting of the bridges (216-7 with fig. 1).

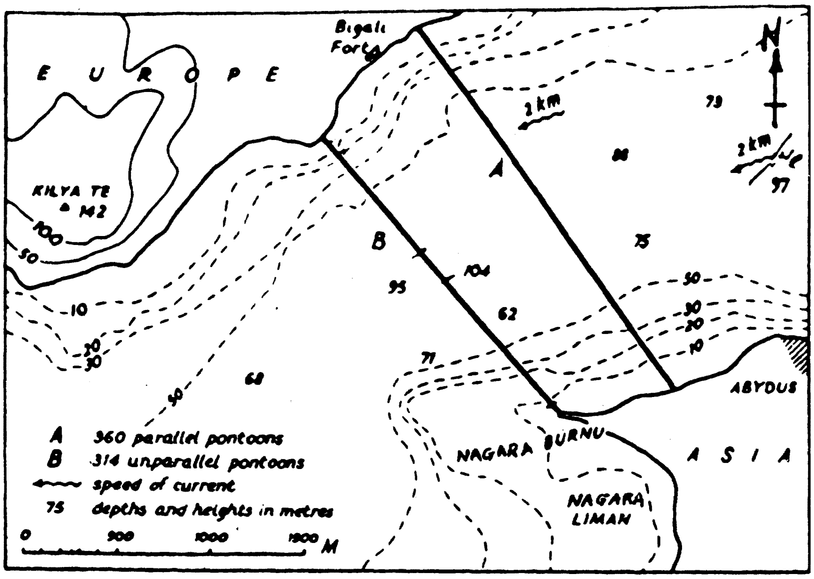
[12] Thus corn-barges, running downstream, would have used a central opening in the bridges where the current ran fast, whereas the light craft, going up the Hellespont, would have used openings near the coast and taken advantage of the counter currents.

[13] Burn 320 judged the cables to be continuous and so 'about a mile long', and he reckoned that the heavier kind of cable would have weighed 'close on 100 tons'.

The landward ends of the roadway which was to lie on top of the taut cables were not described by Herodotus. We may suppose that on the south side the roadway was entered from the low-lying ground of Nagara Burnu and of the nearby plain (see B 2 above). On the European side, the northern end of the western bridge would have led onto the firm gravelly beach, and that of the eastern bridge would have reached the foot of the hill where the Apobathra was located. But the level of water was lower in ancient times, as we have noted.

Map: Xerxes bridges at the narrows of the Hellespont, based on British Admiralty Chart No. 1429.

Note:
In the time of Xerxes, the coast at either end of Bridge B was roughly the 20 metres dotted line, and the coast at either end of Bridge A was very roughly on the 30 metres dotted line. In the map, the bridges are shown extending from present shorelines, so that the reader can visualize them more easily.



Herodotus was more interested in the materials used for the six cables of each bridge, and in the weight of the flax-cables. Where did he obtain this information? The answer is probably Samos, where he may have lived as a young man some twenty years after the building of the bridges; for Samos was the home of Mandrocles, the architect of Darius' bridges, and perhaps also of Harpalus, one of the architects of Xerxes' bridges (Hdt. iv 87-9 and *Laterculi Alexandrini* 8, ed. Diehls), and it is certain that Samos was one of the subject-states which provided manned warships for the bridges. For that reason the cubit was probably the royal Samian cubit of 527 mms. (H. and W. i 138), and the talent was that of Samos, namely the Euboic talent, which was in Ionia 'the basis of all calculation' (C. Seltman, *Greek Coins* [London 1933] 37). This talent weighed about 25.86 kilogrammes = 57.01 lbs. Herodotus made the point that the cables of flax were heavier than those of papyrus 'relatively' (LSJ s.v. λόγος ii 1), which I take to mean individually and not, as H. and W. ii 144 argued, 'the four byblos (papyrus) cables were absolutely heavier than the two esparto-grass', which would have been a glimpse of the obvious.

7. With the pontoons anchored in place and the cables taut over them 'the strait was bridged'. Next, as I understand the passage, they made planks as wide as the tree-trunks, placed a number of planks together so as to equal the width of the 'raft', i.e. the pontoon whether a trireme or a penteconter, and arranged the groups of planks in order on top of the cables and joined the groups together 'at the top', probably with a loose tie. The aim was to have the planking flexible where it passed from one pontoon to the next pontoon, so that, if one pontoon should rise and its neighbour should fall somewhat, the planked roadway would not be disrupted. The addition of brushwood and then of compacted earth provided the continuous roadway which ran

on over the junction of one pontoon and its neighbour and which rested on the cables. The result was a natural track for cavalry horses and for draught animals yoked to a waggon. The palisades were erected at the edges of the planks.[14]

8. Herodotus used different expressions when he described (1) the destruction of the original bridges of Xerxes and (2) that of the bridges used by the army crossing to Asia. For (1) he used two verbs συνέκοψέ τε...καὶ διέλυσε (vii 34), where I suggested that συνέκοψέ meant the snapping of the cables. For (2) he used only one verb διαλύω. The implication is that in (2) the cables were not snapped. Both pontoons and cables were parts of 'the bridges' which had previously been 'taut' (ix 114).

9. The cables from the bridges (ix 115 τὰ ἐκ τῶν γεφυρέων ὅπλα) were safeguarded first at Cardia and then at Sestus as the best fortified stronghold, in case they were needed for the construction of other bridges. Since they had been secured to land-piers, they had not been carried away by wind and wave during the storms. Thus there were twelve cables, each 1,500 m. long, at Sestus. When the Athenians sailed from Sestus to Athens, they took presumably only a section or two of the cables to be offerings to the gods.

10. Aeschylus probably served in the fleet which laid siege to Sestus in 479/8 BC. He produced his *Persae* in 472 BC, when many of his audience had seen the cables and the sites of the original bridges. Aeschylus referred to the distinctive features of Xerxes' bridges: (1) 'a raft' (σχεδία); (2) 'flax-bound' (λινοδέσμῳ), 'finely-wrought ropes' (λεπτοδόμοις πείσμασι); (3) 'people-carrying devices' (λαοπόροις μαχαναῖς), 'a much-bolted way' (πολύγομφον ὅδισμα), and 'a great pathway for a great army' (πολλὴν κέλευθον πολλῷ στρατῷ). Of these phrases the third group referred to the skilfully devised roadway. In the first and the second we have the two main features of the structure, as in the account by Herodotus. In addition, Aeschylus seems to have referred in an allusive phrase to Xerxes' landing-place, the 'Apobathra', when he wrote that 'the host together with its commander, having passed the sea-washed promontory which yokes both sides in common of either continent, has disappeared' (τὸν ἀμφίζευκτον ἐξαμείψας ἀμφοτέρας ἅλιον | πρῶνα κοινὸν αἴας, vv.131-3); for no news of what had happened in Europe had reached the capital at Susa.

11. Arrian seems to be in error. His phrase 'the warships being set together with ropes' (ξυντεθεῖσαι αἱ νῆες σχοίνοις) implied that the ropes tied the ships one to the other (see C 3 below). That is not what Herodotus wrote; for at vii 36.1-2 there was no mention of cables (see B 4 and 5 above). Arrian was probably misled by his knowledge of the Roman method of bridging wide rivers, according to which one ship was tied to another by planks (*Anab.* v 7.4). Myres made the same mistake: 'the ships (of the eastern bridge) were lashed four-square to the cables' and 'the remedy was to lash each ship first by the bows to the upstream cable ... and to lash it astern to the downstream cable' (222). He thought too that 'each bridge, being to leeward of the other, needed no moorings on its own inward side', as if a northerly wind and a southerly wind were blowing simultaneously and meeting one another at the bridges continuously. Macan, followed by H. and W., thought that each cable consisted of eight or ten separate pieces, and that each piece tied a number of pontoons together, which could be moved about as a unit, a sort of 'mulberry' in the terms of 1944. H. and W. put forward an

[14] Herodotus vii 55.1 reported that the armed forces and Xerxes himself crossed on the eastern bridge, while the draught animals and the retainers crossed on the western bridge. If the camels crossed on the latter bridge, the palisade would have been high to prevent them seeing the water. On the other hand they might have been transported by ships, for the fleet was also available.

incongruous argument. 'If Herodotus means that the cables were all in one piece, he is of course wrong as the weight would be too great; doubtless each was made in eight or ten pieces; the length of modern cables is 720 ft.'(ii 144). The weight of a cable was the same whether it was in one piece or in ten pieces, and the length of modern cables is irrelevant.

Additional comment. R. Macan criticised Herodotus for not explaining in his account how the warships were manoeuvred into position alongside one another. What Herodotus did tell us was that 674 penteconters and triremes were provided on Xerxes' orders by some of his subject states (vii 21.2). We can guess that those states included Greek states in the islands and in Asia which were under Persian rule. These ships were of course manned, were brought by their crews to the Hellespont, and were therefore manoeuvred by them into the two lines. No doubt one warship was towed into position by a warship under oar, was anchored, and then set free. Arrian described a similar technique in Roman times (*Anab.* v 7.3). There are of course other points which we should like him to have told us: for instance, how the cables and the capstans were secured on land, whether all the pontoons were anchored bow and stern, whether the very long anchors were additional to these, and so on. But we have to remember that Herodotus was not writing a monograph on the construction of these bridges. Instead he told us what he judged would enable us to understand how the Hellespont was bridged and how Xerxes' army was able to cross from Asia to Europe in seven days and seven nights (vii 56.1). How wide, for instance, was the roadway? The Greek road from the Megarid towards Plataea which was used by waggons in 479 BC was some 9 ft. wide, and a later road near the top of the pass through Mt. Gerania averaged some 12 ft. wide. Because penteconters, even when not at right angles to the line of the bridge, could accommodate a roadway of 12 ft., I suggest that the roadways on Xerxes' two bridges were of that width.[15]

C. Feasibility of the Reconstruction

The bridges described in Herodotus were well within the capacity of the engineers of the day to design and build. Herodotus' description provides the clues to the design but, since he was not an engineer, those clues are ambiguous and have given rise to several varying interpretations of the bridge's construction. Joining basic engineering principles to Herodotus' account allows us to create a credible reconstruction: we argue that Herodotus was describing the construction of a pontoon bridge, the cables for which were made in place. The cables are the key to this argument.[16]

[15] This would allow for a column of four armed men abreast and of two cavalrymen abreast. Maurice thought of 'a column of troops in fours' at narrow places on the route, of which the bridge-roadways are examples. It is thus credible that the crossing of the two bridges did take a week, day and night.

[16] Basic articles in the *Encyclopaedia Britannica* 1957 and 1993 describe a process which is entirely compatible with Herodotus' account. Both show that 'capstans' ('donkeys') are used in several phases of the manufacturing process: 'Friction on the revolving capstans draws the yarn through the machine' (1957, xix 546). 'Strands also known as readies are formed by twisting yarns...together' (1993, x 176). Three or more strands are twisted (laid) into a rope (the 1993 edition is more apt to use the word 'flyer' than capstan). 'The three subassemblies of the rope-laying machine arranged in tandem horizontally, are the foreturn flyers (rotating strand bobbins), the capstan flyer (pulling mechanism), and the receiving flyer (rope-twisting and storage bobbin mechanism)' (1993, x 176). Instead of winding the rope 'onto a heavy steel bobbin', the floating 'raft' was used as a 'ropewalk' (before removing any ships to make the gaps described in Herodotus) over which the rope was laid *in situ* and the final capstan was on land. It should be noted that any twisting of a finished cable or rope will either create kinks or unlay (unwind) the strands of the rope. Therefore, the words of Herodotus *cannot* be describing what was done to the finished cables.

1. Feasibility of making cables *in situ*

The elements of a cable are ropes, made in three basic stages. First, raw fibres are spun into yarn by twisting together a continuous series of overlapping fibres so that the force of friction will grip them and provide its strength. Second, a chosen number of yarns are twisted together to form a strand in a manner similar to that of spinning yarn, except that one starts with 20, 30 or more twisted yarns instead of a series of loose fibres. And third, strands are 'laid' or twisted together to form a rope in a process called 'closing the rope'. Most ropes have three strands. The key to cohesion is in the direction of the twist. At each of the three stages the twist is in a different direction: the strands are twisted against the direction of the yarns and the rope against the strands. The result is a balanced energy pattern which stops any tendency for the rope to unwind.

Using those tools, techniques and material handling capacities available at the time, we can reconstruct a process of cable-making for the bridge. It would seem that bales of fibre were brought to the bridges' site in ships. First the bales were opened and sorted into bundles small enough for one man to handle. Then the flax was drawn through a coarse 'heckle' (some call it a hatchel) which is a wooden board with perhaps forty iron pins, each a foot long, arranged in rows—one side inclining from the workmen. The men would grasp a handful of flax and draw it through the heckle pins, dividing the fibres, cleaning and straightening them in preparation for spinning.

Spinning frames would be erected on land (in pits similar to that of FIG. 4 but upright) well back from each bridge-end. We may think of a frame technologically akin to those of the early 1800s, which had eight hooks extending from the rim of a stationary wheel, each hook inserted into a small capstan on the other side of the rim. The capstans were rotated at a very high speed by a pulley rope connected to a large driving wheel turned by hand. Each spinner would wrap a bundle of fibre around him and, taking hold of the middle of the fibres, attach them to the rotary motion of his hook that supplied the twist. As the hooks spun, he would walk backwards away from the frame, keeping the fibres taut. With one hand he would feed new fibres from his bundle into the forming yarn and with his other hand he would keep the newly spun yarn round and smooth. All spinners would walk backwards the full length of the pontoons 'extending the yarns from the land'; a simple yoke with men at either end walking forward and a harness in the center around a spinner would provide stability when moving from one ship to another or when the ships moved up and down. When they reached the opposite spinning frame, the yarns would have been taken off the hooks. So that the yarns would not sag on the ship decks, they were supported (every few yards) by trestles with vertical pegs on them to separate the yarns. The spinners were able to continue making yarn by using the spinning frames positioned on the 'far' shore and working their way back to the 'near' shore. This process continued until all the yarn required was spun; to account for subsequent twisting operations, it would be much longer than the finished cable. The 125 ft. length of each penteconter, tied to adjacent ships, created cross-channel pontoons which could accommodate several spinners working side by side with multiple spinning frames erected at each bridge site to speed the process.

The number of yarns per strand for our cable can be calculated by reference to early modern rope-making; 'To find the number of yarns . . . per . . . strand for any three-strand cable laid: multiply the square of the cable by the size of the yarn, and divide by 36.'[17] For our 27 in. cable (see C 4(2) below) and assumed yarn:

[17] Robert Chapman (formerly foreman to Mssrs. Huddart & Co., Limehouse; and Master Ropemaker of H.M. Dockyard, Deptford), *A treatise on ropemaking as practiced in private and public ropeyards, with a description of the manufacture, rules, tables of weights, etc., adapted to the trade, shipping, mining, railways, builders, &c.*, (Philadelphia 1869) 22.

$$\frac{(27)^2}{36} \times 18 = 364 \textit{ yarns per strand}$$

Before recent technological developments, a strand had to be made by 'attaching' the required number of yarns to one hook on a stationary 'donkey' and to another hook on a travelling 'donkey'. The stationary 'donkey', anchored in the ground in a rock lined pit, had the capacity to twist the yarns together by a rotary motion which contracts the forming strand and pulls the travelling 'donkey' towards the stationary 'donkey'. The yarns on the outside of the strand would bear more stress than the others and would break first. The object is to maintain a certain speed in a given time with respect to the travelling 'donkey', in order that the strand will receive a proper degree of twist in a certain length.

The third and final stage is that of 'closing' or laying the rope. At the 'near' shore were the stationary 'donkeys', and at the 'far' shore the travelling 'donkeys' were set up as sledges on smooth surfaces. Each pair was connected by a continuous drive-rope taken round capstans at the 'far' shore end of the rope walk. These capstans were operated by hand winches, with up to 220 men employed to close such large cables. The strands to be made into rope were laid out along the rope walk, supported and kept apart by the trestles, their ends connected to separate hooks on both the stationary and travelling 'donkeys'.

The first phase of this third stage was to 'tension' or 'harden' the strands, done by turning the hooks of both donkeys in a clockwise direction. As the strands were twisted they shortened and became tense. When the ropemaker in charge felt that the strands had received sufficient hardness of twist, the hooks were stopped: at the travelling donkey, the three strands were placed upon one hook; at the stationary 'donkey', the three strands remained on separate hooks. Then a cone of wood—a 'top', with three grooves cut into it to receive the strands—was inserted between the strands a short distance from the travelling 'donkey'. The 'top' acted as a guide which caused the strands to come together evenly. When the 'top' was fitted between uprights of an arch, then mounted on a horse, the hooks at both ends of the ropewalk were rotated. The travelling donkey had its hook put into reverse, so that it turned in an anti-clockwise direction, twisting the strands together into rope as they passed through the top-grooves. This action forced the 'top' (with the horse supporting it) down the ropewalk, and the ropemaker in charge walked alongside the horse, controlling the speed by means of a small piece of rope twisted around the newly formed rope. As the strands combined to form the rope, the distance between the two donkeys shortened, pulling the travelling 'donkey' down the 'far' shore. Weights were placed on the sledge to maintain tension in this phase. During closing, the strands were twisted together in the opposite direction to that of the forming process. To prevent them from unwinding, the hooks of the stationary donkey continued to turn in a clockwise direction. Once the 'top,' mounted on the horse, had travelled the length of the ropewalk, the rope had been made. The ends were tied off to prevent unravelling and then the hooks cut off. Then the 'spliced eyes' were completed at either end of a cable and inserted in the end restraint configuration of C 5.

The above reconstruction has been reviewed by England's last remaining Master Ropemaker, Mr. Fred Cordier who has spent 29 years (since a small boy) working at the Chatham Historic Dockyard, Kent. He has served in all phases of ropemaking, and today heads the ropewalk workforce. Mr. Cordier finds no fault in the concepts proposed here and while not being able to 'approve' some unknown details, he feels men of 480 BC could have made the cables *in situ*.

The cables were crucial to the bridge construction but there were several other, equally essential, elements: penteconters and triremes, anchors, roadway and end-restraints.

2. The Penteconters and Triremes

These represent the pontoons or rafted floats. Most of the ships are likely to have been penteconters because they were lighter and thus would offer less resistance to the currents. According to L. Casson 'a single-banked penteconter would run some 125 ft. in length. The beam would be about 13 ft.'[18] Triremes were probably used only at either side of the gaps, both for additional height (i.e. 8 ft. 6" waterline to deck) and to handle the extra loading.[19] Each trireme would handle one-half of the load over the gap, plus that sustained on its 16 ft. wide deck. The total weight of the bridge was supported by all the penteconters' and triremes' buoyant capacities which are well within any possible loadings. (See maximum loading configuration below).

3. The Anchors (fore and aft) (Fig. 1)

These were no doubt the design with removeable stock: the words 'very long anchors' (A 5 above) refer to the length of stock. As Casson points out (253), 'The essential weight the ancients put into the stock—the reverse of subsequent practice which was to put it principally into the arms and shank.' What he does not say is that they did not use chain in their 'ground tackle' (a general term for anchors, cables, chain, etc., anything used in securing a vessel at anchor) until years later. So the function of keeping the pull on the arms as horizontal as possible was performed by a heavy (removeable) lead stock, allowing the arms to 'stay put' or 'bite' and not lift out. Anchor dragging is the result of rope lines floating and lifting out the arms from their holding locations; thus, holding power is proportional to the area of buried arm multiplied by the distance it is buried into the bottom. One of four components making up the load on an anchor is the wind pressure. Another component is the load due to current, equal to the resistance of the vessel travelling through water at the speed of the current. The third is the load due to surge while anchoring, and the fourth is the shock load due to the vessel's rising vertically on the sea, trying to lift the anchor.[20] These components can occur singly or in any combination. Any attempt to estimate the load to be resisted by these anchors would thus be wholly inadequate, since all of the factors are unknown for the early fifth century BC. Charles Chapman provides a table of suggested modern anchor weights (104), which for a storm anchor of a boat of 125 ft. would be 300 lbs. Another of his tables shows results of anchor-holding tests (104), with weights up to 31 lbs. Results varied from 9,600 lbs. in hard sand to 1,250 lbs. in very soft mud. These anchor weights are for the modern Danforth anchor and would be grossly inadequate for ancient anchors.

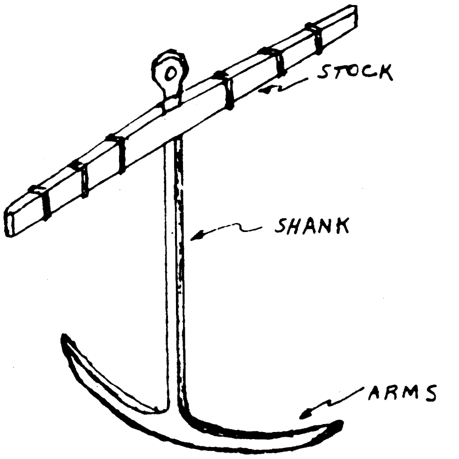


Fig. 1

By placing the ships into prevailing winds, the exposed cross-sectional area above water was minimized. Also, anchoring 'into the current' helped to minimize the ships' resistance. Using mostly fifty-oared ships with lower profile and less draft was in-line with lightening the strain on the anchor cables.

The ships were lashed together to facilitate the laying of the anchors. First, the ship closest

[18] Casson, 54.

[19] J.G. Landels, *Engineering in the ancient world* (London 1978) 145, fig. 52.

[20] Chapman, 103.

to shore would be positioned and its anchors laid fore and aft. Then the next ship would be positioned alongside and lashed to the first one while the anchors from the second ship were placed in small boats and rowed to the appropriate locations fore and aft. The anchors would be lowered and the lines from the second ship pulled in until it was felt that the anchors dug in, a process still in use when many small boats wish to 'raft' together at one location. The lashing together served only the rafting process and would be of no structural significance once the bridge was completed. A solid line of ships was no doubt first laid in place to make the 'rope walk' as explained in B 6 above. After the cables were manufactured, ships could be removed as required for passage. Any lateral loads due to drifting at the passage site could have been addressed by extra lashings when conditions warranted. But it would seem probable that 'the narrow space' (B 5 above) would not be opened during unfavorable conditions.

4. The Roadway

The elements of the roadway are five: cables (six in number), planks, brushwood and earthen tread, palisades, plank joining concept.

Cables

(1) The cables 'of which a cubit weighed a talent' (A 6 above) can be configured using the following data: 1 cubit = 527 mm, 1 talent (Attic/Euboic) = 25.86 kg. = 57.01 lbs. (B 6 above). Thus, Herodotus' cables would have a wt/unit length = 32.97 lbs/ft which for a cable 1,500 m. long = 162,000 lbs. This includes water content as explained below. However, the weight stated in Herodotus was for rope as made *in situ*, which would include water content due to local humidity. A conservative estimate for such a marine location would be an 80% humidity level. At this level, water content of flax will equal 13% of dry measure.[21] Therefore,

$$1\ talent = 57.01\ lbs. = 113\%\ dry\ measure$$
$$and\ dry\ measure = \frac{32.97}{1.13} = \underline{29.176}\ lbs/ft$$

(2) Herodotus provides the unit weight of the cable. How do we determine its size? Using an analogy from the traditional art of rope-making, described in a manual dating to 1869,[22] we can make the following calculations, which are based on dry ropes. For the size of our cable we use: 'Rule for three-strand cable: to find the weight of 120 fathoms, square the size of the cable, and divide by 4.'[23]

$$Thus: \frac{(cable\ size)^2}{4} = X\ cwt.\ (long) \quad where\ 1\ cwt. = 112\ lbs.$$

Since our cable weighs 29.176 lbs/ft (dry), 120 fathoms weighs 187.56 cwt. Therefore, cable size = $[(4)(187.56)]^{1/2}$= 27.4 in. or approximately 27 in. *Herodotus' cables would thus be of a nominal circumference of 27" and a nominal diameter of 9"* (the rope-making industry uses 3

[21] Kutz, fig. 16.9.

[22] Chapman (n. 17) 6: 'This work has been written with the view of assisting the workman in obtaining a knowledge of the calculations necessary to the art of ropemaking; having in the course of my own practical employment, been frequently in want of such rules, and as often been disappointed when asking information of those it might have been expected from, I was in consequence, compelled to form rules to enable me to carry on the work and to answer questions put to me by the officers of the dockyards through the Lords of the Admiralty, and which were often very absurd; hence, the following rules and tables will be found chiefly to consist of those practical rules connected with the art of ropemaking.'

[23] Chapman (n. 17), 29-30.

as a conversion between circumference and diameter since a true cross section of a rope is not a true circle).

(3) For the tensile strength of our cable we use:
'Rule to calculate the tensile strength of a three-strand cable: square the size of the cable, and divide by 5.'[24]

$$\textit{Thus: } \frac{(\textit{cable size})^2}{5} = X \textit{ tons (long)} \qquad \textit{where } 1 \textit{ ton} = 2{,}240 \textit{ lbs.}$$

$$\textit{Thus, breaking strength} = \frac{(27.4)^2}{5} \times 2{,}240 = 336{,}000 \textit{ lbs.}$$

However, these rules reflect the use of Joseph Huddart's register plate and forming tube, invented in the 1790s. Their introduction doubled the strength of rope.[25] Therefore, dividing by two gives breaking strength = 336,000/2 = 168,000 lbs.

(4) The material about which Robert Chapman writes is hemp and our cable is flax. However, the density of hemp is exactly equal to that of flax,[26] resulting in the same weights.

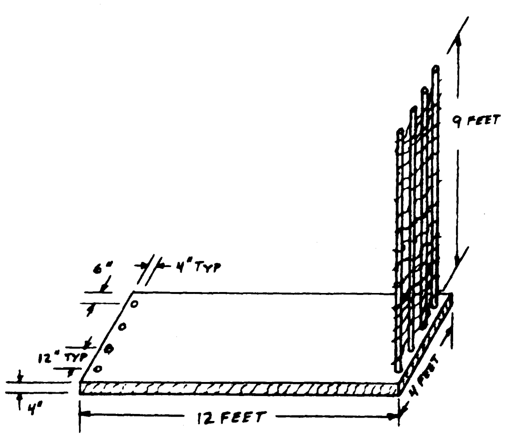


Fig. 2

Planks
The main bearing loads for traffic across the bridge were sustained by the planks cut from tree trunks. Hull planks of ships were made from fir, pine, cedar, and larch, but fir was the first choice.[27] It would follow that the first choice for roadway planks would also be fir. The width of planks taken from fir would be limited to about 4 ft. due to the natural size of the species. The length would be about 12 ft. (B 'Additional Comment' above). Thus, the roadway would be 12 ft. wide. The thickness of these planks would be in the order of 4 in.[28]

Brushwood and Earthen Tread. The brushwood is not described but can be envisioned to serve to span the gaps between planks, as well as a 'grid' to hold in place the layer of compacted earth laid over it.

Palisades. B 7 says 'the palisades were erected at the edges of the planks.' One configuration could be as shown in Fig. 2. Holes were drilled 4 in. from the edges at the spacing shown, with tree limbs of about 1 or 2 in. in diameter (at one end) thrust through the holes and lashed

[24] Chapman (n. 17), 31.

[25] Richard Holdworth and Brian Lavery, *The ropery visitor handbook* (Chatham [Kent] 1991) 12.

[26] Kutz, table 16.75.

[27] J.S. Morrison and J.F. Coates, *The Athenian trireme* (Cambridge 1986) 180.

[28] Ira Osborn Baker, *A treatise on roads and pavements* (New York 1908) 274: 'Plank roads were once somewhat common in the heavily timbered portion of the northern United States and of Canada. The first plank road on the continent was built in Canada in 1836... The method of construction most commonly followed is to lay down lengthwise of the road, two parallel rows of plank called sleepers or stringers, about 5 ft. apart between centers, and upon these to lay cross-planks 3 to 4 in. thick and 8 ft. long... The planks were often covered with gravel, sand, or loam to protect them from wear. ...when kept in repair, plank roads make a comparatively smooth roadway possessing some advantages for both heavy and light traffic...'

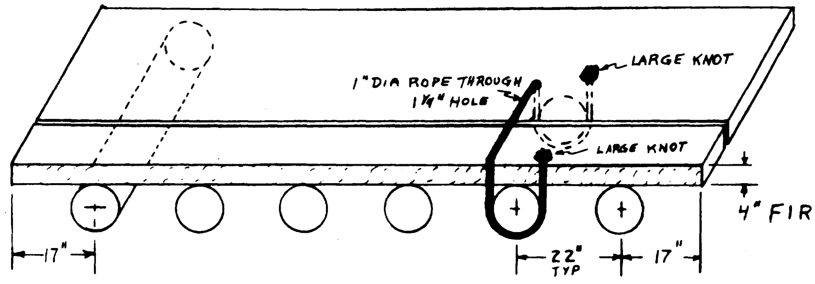


Fig. 3

together above and below the plank. Then smaller limb pieces with leaves were woven between the uprights, and additional brushy ferns added to make a solid screen 9 ft. tall.

Plank joining concept. B 7 says ' ... each plank being joined to its neighbour "at the top".' One configuration could be as shown in Fig. 3. Two holes of 1.25 in. diameter would be drilled at each cable location (adjacent to the cable and 4" from the plank edge), with a one inch diameter rope passed through one hole, down and round the cable. Coming up the other hole in the same plank and over to the next plank, it then passed down and around the cable, and up through the fourth hole. Finally, a large knot would be tied in one end, and after pulling tight (to draw the cable up against the planks) another large knot would be tied in the other end (just above the plank surface). This arrangement stitched the planks together at six places and secured them to the cables at either side of the 'joint'. While only one cross-link per location would have been achieved, the total of six 'stitches' would have provided about 12,000 lbs. of tension capacity.[29] This design has the advantage over a continuous stitching concept in providing independent backup capacity in case of failure at one location. One failure in a continuous lacing concept would result in total rupture of the joint.

5. Configuration of End Restraints

The revelation that rope was being made in place, across the rafts (serving as a ropewalk), allows the description of the terminals as 'spliced eyes'. These eyes retain 95% of the rope's original strength.[30] A 'spliced eye' can be made with any size opening allowing a wrought iron post to be placed through it. Herodotus mentions in i 68 the journey of Lichas that brought him to Tegea. Here he 'watched the forging of iron...'. Since Lichas lived during the reign of Croesus, we know wrought iron was being made *c.* 560-546 BC, which of course predates the building of the bridges at the Hellespont. The post could then be lashed to a team of horses and pulled as it was positioned into a stone-lined shaft. Any desired pre-tensioning could have been done by this process; however, from a load-carrying capacity standpoint, no large pre-tensioning was required—or desired. In fact, since positioning of the cable ends should have been accomplished before adding the planks, brush, earthen tread or palisade, significant tension would have been introduced with the addition of all that weight bringing the cable down to rest firmly on the raft of boats. The details could be as shown in Fig. 4. The wrought iron post would be sized to accommodate two parameters, structural capacity and space limitations. If we

[29] 1" dia. approximately 3" cir. Breaking strength = 4,032 lbs. (per Chapman [n. 17]). Total breaking strength per joint = $\frac{4,032 \times 6}{2}$ = 12,000 lbs.

[30] Chapman, 197.

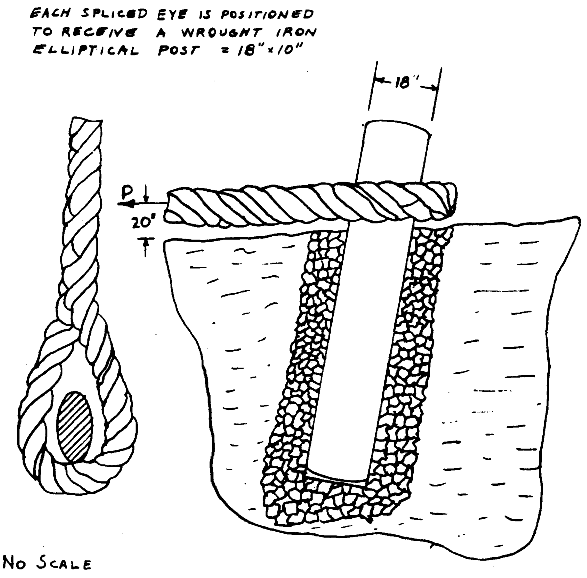


Fig. 4

take the load 'P' of Fig. 4 to be that which ruptures the cable, and does not cause the post to fail or bend, we produce a configuration which retains the cable, and *not* the post, as the weak link. To that end we offer the elliptical shape 18 x 10 ins. The post would have been secured in a rock lined shaft to ensure the constraining moment of a cantilever beam. The maximum stress (Max s) would have been equal to the applied moment (M) divided by the section modulus (I/c) of a solid ellipse 18 by 10 ins.

$$\textit{Thus}\quad \textit{Max s} = \frac{M}{I/c} = \frac{168{,}000\ \textit{lbs.} \times 20''}{\dfrac{2862.8}{9''}} = 10{,}560\ \textit{lbs. per sq. inch}$$

Minimum stress to bend wrought iron = 25,000 lb. per sq. in.[31] Space requirements would be met by staggering the six posts. Then we would have the result shown in Fig. 5.

6. Bridge Analysis

Maximum Load Configuration. The maximum loading condition for a 13 ft. wide penteconter when being used as a bridge pontoon is made up of the following elements:

cables	13 x 32.97 *lbs/ft* x 6	2572
planks	$13 \times \frac{4}{12} \times 12 = 52.0\ ft^3$ @ 39.96 lbs/ft^3 [32] (*Assume* 13 *ft. of solid board*)	2078
brushwood	(*Assume equal to* 1" *thick board*)	519

[31] *Marks standard handbook for mechanical engineers*[9] (New York 1987), table 5.1.1

[32] *Civil engineer's reference book*[4] (London 1989), table 31.6 'Timber properties'.

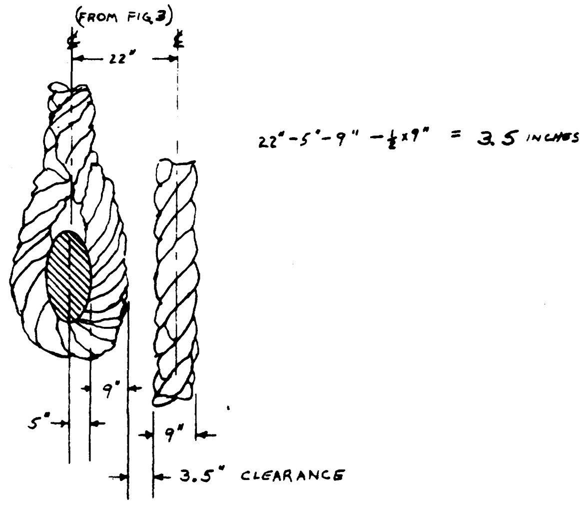


Fig. 5

earthen tread	$13 \times \frac{3}{12} \times 12 = 39.0\ ft^3$ @ 125.0 lbs/ft^3 [33]	4875
	(*Assume* 3" *of pressed loamy earth*)	
palisades	$13 \times \frac{2}{12} \times 9 = 19.5\ ft^3$ @ 39.96 lbs/ft^3	779
	(*Assume each side* = 1" *thick board*)	____
	Total Dead Weight =	10823 *lbs.*

live load (*including dynamic loading* @ 2 *g's*)

2 x 2 *abreast Nesaean horses* @ 1,000 *lbs.*	4000
2 x 6 *men* (2 *ahead,* 2 *abreast,* 2 *behind*) @ 175 *lbs.*	<u>2100</u>
Total Live Weight =	6100 *lbs.*

When the dead weight and the live weight are added together, the total maximum load on the penteconter is <u>16,923</u> lbs.

The maximum loading condition for a 16 ft. wide trireme when being used as a bridge pontoon is the same as that for a penteconter per foot. But, instead of carrying only the 13 ft. loading of a penteconter, it carries the loading for its width of 16 ft. plus half the loading for the adjacent 16 ft. gap, or 24 ft. Supporting ramps would have been built in those locations where deck levels were uneven in order to assure uniform loadings. Thus the maximum load which a trireme has to carry is:

$$\left(\frac{24}{13} \times 16{,}923\right) = \underline{31{,}242}\ lbs.$$

[33] N.A. Lange, ed. *Handbook of chemistry*[6] (Sandusky, Ohio 1946) 1356.

Rather than attempting to calculate the capacity of these ships to sustain loading, it is possible to show from evidence in Herodotus that these maximum loads have been exceeded in actual use in antiquity. Herodotus (i 164.3) gives an idea of the capacity of a penteconter. In 540 BC, when the men of Phocaea on the coast of Asia Minor decided never to submit to Persia, 'they put on their penteconters their "children, women, all movable property" and some sacred objects, and they set sail for Chios.' Each penteconter was rowed by fifty oarsmen, and these men were accompanied by their families and possessions. If we assume that the average family consisted of the equivalent in weight to the weight of two and half men, and that the possessions plus the water and the foodstuffs for a voyage weighed half a man in each case, we shall arrive at a load for each penteconter, apart from the oarsmen, of the weight of 150 men. Thus, when we add the oarsmen, the total load is equivalent to 200 men. This is, of course, a very rough estimate, but it is adequate for our purpose. Additionally, each ship required basic 'running gear', i.e., oars, anchor lines, anchors, mooring lines, steering oars, a mast, sails, rigging, pulleys, etc. Thus weights for a penteconter in use:

crew (50) @ 150 *lbs. ea.*	7,500	
load: weight of 150 *men* @ 150 *lbs. ea.*	22,500	
oars 50 x 4.6 *kg.* [34]	500	
anchor lines 6" *cir*, 2 *lines*, 200 *ft. ea.* [35]	500	
anchors 2 @ 40 *lbs.*	80	
mooring lines 4.5" *cir*, 2 *lines*, 100 *ft. ea.*[36]	140	
steering oars (2) *assume equal to* 3 *rowing oars, weight ea.*	60	
mast, sails, rigging, pulleys, etc.	500	
penteconter calculated usage =	31,780	*lbs.*
(*from p.*103) *maximum loading =*	16,923	*lbs.*

Similarly, two other passages give the crew (vii 184.2) and fighting men (vi 15.1) numbers for a trireme in normal use. These, and the basic 'running gear' numbers provide weights for a trireme in use:

crew (170) @ 150 *lbs. ea.*	25,500	
fighting men (40) @ 160 *lbs. ea.* (*w/swords*)	6,400	
oars (170) x 4.6 *kg.*	1,720	
anchors, anchor lines, mooring lines, steering oars, mast, sails, rigging, pulleys, etc. (same as penteconter)	1,280	
trireme documented usage =	34,900	*lbs.*
(*from p.*103) *maximum loading =*	31,242	*lbs.*

Load Path Analysis. We consider now whether a whole bridge can sustain the total load, composed up of a vertical and a horizontal load.
Vertical: This component, distributed as a varying uniform load, produces reactions from ship buoyancy and, where the bridge is over land, the basic soil-bearing strength (Fig. 6).

Horizontal: A horizontal component also distributed as a varying uniform load is due to wind and water current forces. Reactions to these loads are from anchor line tensions and the holding

[34] J.F. Coates, S.K. Platis, and J.J. Shaw, T*he trireme trials, 1988* (Oxford 1990) 52 describes advanced oar design weighing 4.6 kg. This figure is used both for the penteconter and the trireme oars.

[35] Casson, 250.

[36] Casson, 250.

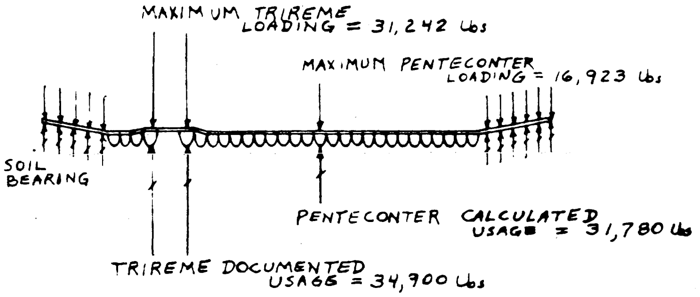


Fig. 6

power of the anchors. No reactions can be provided by the roadway cables.[37] (Fig. 7.) A secondary horizontal component, at right angles to the wind and current loads, is due to strain in the roadway cables as a result of ships moving up and down (due to wave action or local vertical loading). The resulting tension in the roadway cables is reacted through the end restraints (analysed on p. 102).

Category of Bridge. A simple analysis of the total dead weight of the roadway reveals further reasons for concluding that Xerxes' construction was a pontoon bridge.

$$\textit{Roadway length} = 1{,}500\ m. \times 3.28\ ft/m. = 4{,}920\ ft.$$

$$\textit{Total Dead Weight} = \frac{10{,}823}{13}\ (p.103) \times 4{,}920 = \underline{4{,}096{,}000}\ lbs.$$

$$\textit{Total Breaking Strength of cables} = 6 \times 168{,}000\ (p.100) = \underline{1{,}008{,}000}\ lbs.$$

Modern day use of 'factors of safety' would dictate a minimum F.S.=5.0 and if human life were in danger, F.S.=10.0. The minimum F.S.=5.0 would reduce the total allowable working load, at each end, to

$$\frac{1{,}008{,}000}{5} = \underline{202{,}000}\ lbs.$$

Thus, the mere dead weight of the roadway is greater than the total capability of the cables, a characteristic of pontoon and *not* suspension bridges: the weight is simply too great to be suspended.[38]

7. Failure Analysis

The sequence in which elements of Xerxes' bridges failed can be envisioned as a reverse structural analysis of the assembly. That is to say, the weakest part will fail first and the strongest last. The loading condition will be a combination of the wind loads from the storm, creating direct horizontal loads and indirect vertical loads from wave action, and the dead weight loads of the bridge.

So let us visualize the scene. The wind is kicking up the water, causing waves of 6-8, maybe,

[37] If the roadway cables are attached to the boats (which they are not), the end restraint concept would be an inefficient manner to react what would then be additional tension in these cables. Perhaps they were attached in the first design of Herodotus vii 34 in which 'all' was lost. But they were not attached in the second design of Herodotus vii 36 so that the cables were still there in Herodotus ix 114. This allowed Oeobazus to have cable (at least pieces) to carry to Sestus.

[38] In a suspension bridge, half of the dead weight (2,048,000 lbs.), plus half of the live load (1,150,000 lbs.) would be supported (i.e., reacted) at each end. Since the present reconstruction allows for only 202,000 lbs. of allowable working load at each end, this is clearly *not* a suspension bridge.

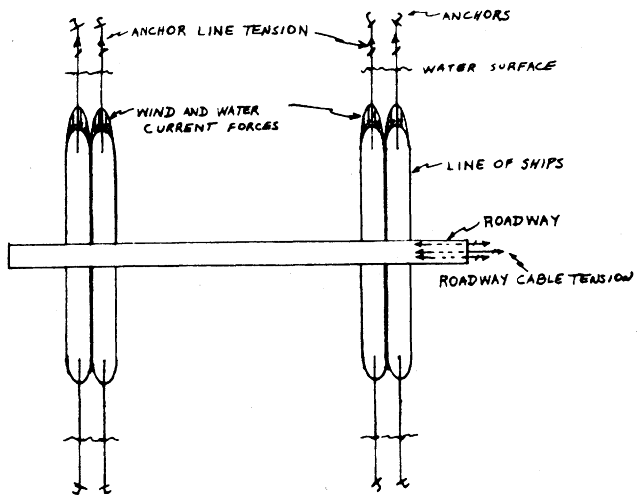


Fig. 7

10 ft. in height. The ships are bouncing up and down as well as against each other, all the while pulling at their anchors. The roadway dead weight is accelerated by the wave action and increases the downward thrust on the underlying ships. Rain may be pelting slantwise against the whole scene.

First, the palisades are blown away exposing the earthen tread to wind and rain. These forces soon scour the loamy earth away, attacking next the light underlay of brushwood, thus exposing the knots holding the walkway planks to wind-driven sand which cuts them like a knife. With no restraints to hold them in place, the planks become airborne 'missiles' weighing some 640 lbs. each with dynamic factors in excess of 5 g's. These planks randomly smash against the ships, acting with devastating effect. Even if the anchors held, the combination of flying planks, pounding wave action and adjacent ship-crunching would soon break up the formation and shatter the ships themselves. This would have left only the massive walkway cables still hanging together, provided they were not tied to the pontoon formation. However, the first set of bridges may have had their cables tied to the ships which would only serve to destroy them, as the cables would have been of smaller size which could not stand the vertical loading due to bouncing wave action. In the case of the second set of bridges, the exposed cables would not have experienced wind resistance forces large enough to rupture them (B 8 above).

No doubt, both cable size and anchor weights were increased by some significant amount as the new engineers tried to impress Xerxes with their improved bridge design. In fact, these are the only elements which could have been enlarged to increase the chances of survival.

D. Summary of the Main Arguments

We began with a close examination of the text of Herodotus, since it forms the basis of any reconstruction. It revealed the point that the cables of the first two bridges were destroyed. Twelve new cables, each 1,500 m. long, had to be provided. Where were they made? As a finished cable in humid conditions would have weighed not less than 162,000 lbs., it would have been laborious to manhandle and transport such a cable from Phoenicia, for instance, to Abydus. It was simpler to make it where it would be in use. It could have been made either on one shore, from which it would have to be hauled 1,500 m. to the other shore, or directly *in situ* on the pontoon bridge. A close look at Herodotus vii 36.8 and an understanding of how a cable is made (see C 1) enabled us to see that the cable-makers started on one shore ('from land') and worked on the pontoons 'extending while twisting on wooden donkeys (i.e. capstans) the cables' until they reached the other shore. The contemporary tenses (B 6) describe precisely the process of cable-making (C 1 'a number of strands are twisted together to make a rope'). No less important was the realisation that to 'extend and twist' a finished cable by force on capstans would damage the cable irreparably, thus ruling out the standard translation of vii 36.8, that of Rawlinson: 'they made the cables taut from the shore by the help of wooden capstans' (see B 6 and n. 16).

Once a cable was made from shore to shore, it had to be attached to land-piers or 'end restraints' (not described by Herodotus, but see B 6 and C 5). During the attaching process the slack of the cable had to be taken up, perhaps by the method suggested at the start of C 5, so that the cable was 'taut'. The cable's purpose, however, was not to act in suspension; for it could not carry even the total dead weight of the finished bridge. Rather it was, as Herodotus said, to form the basis of the roadway of wooden planking (vii 36.4 'arranged in order on top of the taut cables'; A 7 and B 7), in such a way that the cables not only held the roadway together but also provided the continuity and the elasticity which were needed in the gaps between pontoons (B 7).

The pontoon-bridges had to carry the entire weight of cables, roadway and traffic. Each pontoon, once it was manoeuvred into position, was anchored bow and stern with 'very long anchors' (A 5 and C 3); a study of ancient anchors and their holding power explains the expression 'very long' (C 3).

The above are the essential arguments. We have added the attendant circumstances, such as the configuration of the channel, the behaviour of the currents, and the character of the shores, which enable us to locate the bridge-ends. By far the most important gain is the demonstration in engineering terms that the bridges, which we have reconstructed in theory, would have worked in practice.[39]

N.G.L. HAMMOND
Clare College
Cambridge

L.J. ROSEMAN
University of Washington
Seattle

[39] We owe a special debt of gratitude to Professor Carol Thomas, whose enthusiastic interest and helpful comments have been an inspiration.