Ways & Rails for Slipways for Dry Docking Ships

by

Keith Mackie[1]

1. ABSTRACT

The slipway is the oldest method of dry docking ships. However, at least for more remote sites without heavy demand, even at the present levels of development, they are the most practical and economic system. With proper development of the technology, they can exceed other systems in these aspects.

The slipway, however is the most technically complex of all forms of dry docking and this complexity is not well understood – if it is recognised at all. As a result, it has remained the 'Cinderella' of the industry.

The discussions in this paper are intended to remedy this situation – to expose and illuminate this complexity, provide a basic design guide and show the way to further investigations.

2. BACKGROUND

2.1. Origins of the Slipway

There are two basic types of dry docks in use: the hydraulic systems of graving docks and floating docks and the mechanical systems, of which the slipway forms part together with shiplifts and straddles. It is based on the use of the inclined plane and is the oldest form of dry docking. In the 20th century, the development of the slipway has lagged behind developments in other forms of dry docking. However, when modern technology is brought to bear, the slipway can be the safest and most efficient method of dry docking. In areas of lower demand, for vessels under 1000 tons docking displacement but even up to 5000 tons the slipway can be the most economical system

In the beginning, when vessels were small, they were just hauled up and down the beach – **Fig 1** and **Fig 2** and from this the slipway developed – **Fig 3** and **Fig 4**.

Fig 1: Beaching, Soalara, Madagascar 2012

Fig 2: Beaching, Vilanculos, Mozambique, 2009

The formal slipway probably first came into use in the Mediterranean and for thousands of years[2] the slipway consisted of a sled of heavy timber runners over timber sleepers laid on the beach. Some of these are still in use.

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[2] At least as far back as the Late Bronze Age

Fig 3: Shipsled, Bosphorus, 2010

Fig 4: Shipsled, Chania, Crete, 1986

2.2. Types of Slipway

The slipway in its modern form of a cradle on wheels on rails can be precisely dated to the patent awarded to Thomas Morton of Leith in 1819 (Prosser R.B.1894) and his system came to be known as a 'patent slipway'. The cradles were built of timber baulks with small cast iron wheels set in wheel boxes under the longitudinal baulks. These facilities were always built to the three-way system so that the whole weight of the vessel was carried on the centre, keel way. The outrigger ways were for lateral stability.

Fig 5: Patent Slip Cape Town c 1920

Fig 6: Crandall Railway Dry Dock

In the mid-19th century the Crandall family of Boston, Massachusetts (Crandall 1967) developed their own peculiar system commonly referred to as a 'marine railway' or 'railway dry dock'. They use live rollers instead of wheels and cradles built up aft to a wedge shape so that the line of the keel blocks is level.

During the 20th century steel cradles began to replace timber although in general, the three-way system was retained. The modern trend, however, is to exploit the strength of steel and move to a two-way system where the keel block loads are suspended between the two ways by transverse steel cradle beams.

Fig 7: Modern Slipway, Lamberts Bay, South Africa, 1990

3. WAYS GEOMETRY

Slipways can be laid out as either end haul or side haul. End haul systems have a greater extent into the water area but a much smaller extent along the shoreline. Side haul systems have a relatively short extent into the water – and a concomitant steeper grade – but a much greater extent along the shoreline.

Side haul slipways have a series of parallel ways, normal to the shore, spaced along the length of the cradle, transverse to the cradle.

With end haul slipways the ways are again normal to the shore but parallel to the cradle. They commonly use either two or three ways although more can be used. In the case of a four-way system, the central, keel way is split into two parallel ways a short distance apart. Rails are fixed to the ways, usually a single rail to the outriggers but, on larger systems two rails to the keel way.

Given that the ways profile is never perfect, there is a better load distribution to the ways on a two-way system than on a three-way system and, to a lesser extent, on four-way systems. Given that slipway cradles are unsprung, accuracy in vertical alignment of the ways is paramount and the spreading of the keel load to ways set apart does assist in the load distribution.

Gradient of the ways usually varies from about 1:10 for very small units to about 1:25 for very large units. At the very flat grades some form of downhaul will usually be necessary. The usual grades lie between 1:15 to 1:20.

3.1. Straight Grade Ways

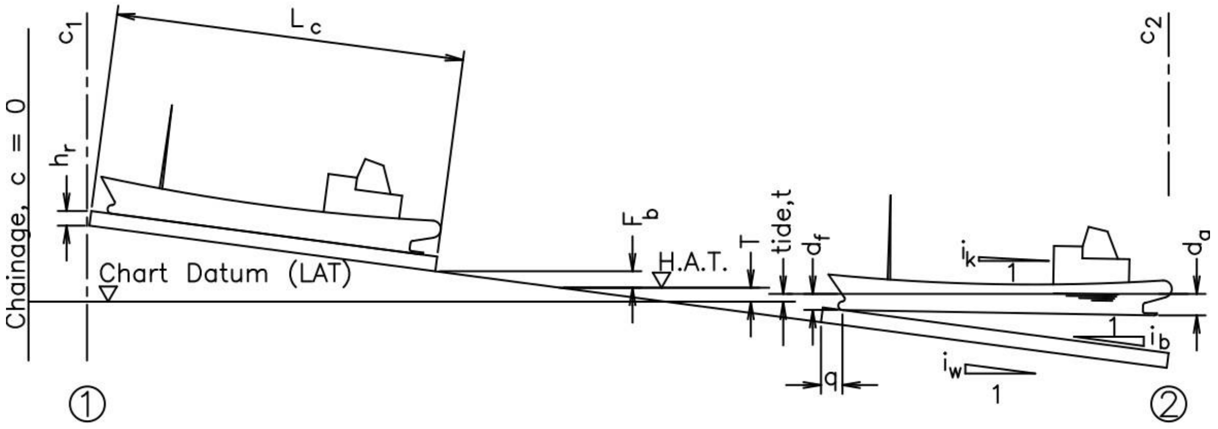


Fig 8: Straight Grade Ways Geomentry

The geometry of the straight grade ways as shown in figure 8 is pretty intuitive and is given for completeness. Given:

c = chainage measured horizontally

c_1 = chainage at landward end of ways

c_2 = chainage at seaward end of ways

h_c = level of ways at chainage c

h_1 = level at landward end of ways

h_2 = level at seaward end of ways

h_r = vertical height of reference block above ways

L_c = length of cradle over blocks

i_w = grade of ways as tangent of slope

i_b = tan of angle between line of blocks and ways

F_b = freeboard above tide

T = max tide range from LAT to HAT

d_f = draft fore

d_a = draft aft

t = stage of tide

Note: the ‘reference block’ refers to the foremost keel block on the front of the cradle

Level, h_c at any chainage c: $$h_c = h_1 + i_w(c_1 - c_2) \tag{1}$$

Chainage c at any level h_c: $$c = c_1 + \frac{h_1 - h_2}{i_w} \tag{2}$$

Horizontal extent of the ways:

$$c_2 - c_1 = \frac{1}{i_w}\left(F_b + T + h_r + d_f - q.i_b\right) + 2.L_c.\cos\tan^{-1} i_b \tag{3}$$

Total slope length of the ways: $$L_w = \frac{c_2 - c_1}{\cos\tan^{-1} i_w} \tag{4}$$

Remember: longitudinal dimensions on the cradle are slope dimensions and do not correlate directly with the horizontal chainage dimensions on the ways!

3.2. Vertically Curved Ways

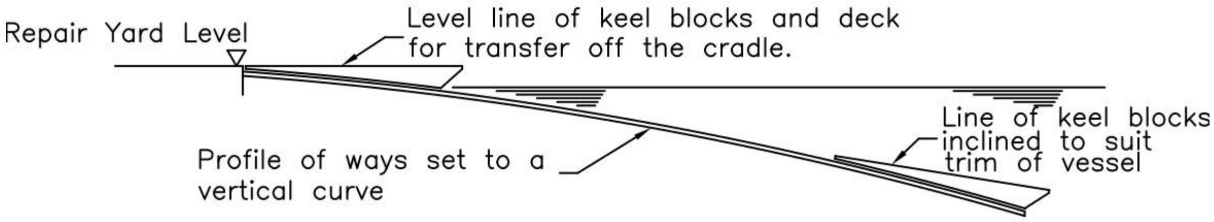


Fig 9: Vertically Curved Ways

Vertically curved ways as shown in **Fig 9**, can make a significant cost saving on the construction of a slipway and improve the operation of the facility. The curve shortens the total length of the ways, reduce the grade of the ways at the landward end and reduces the amount of any rock excavation by bending the ways over the rock.

The computation of the circular curve is complicated by the need to compute the versines (1-cosine) of small angles. It is only with the advent of modern computers that this has become practical.

To determine a suitable ways profile - position and curvature - by trial and error – first establish a site co-ordinate system. Use Chart Datum as the vertical datum, the orientation of the ways as the longitudinal datum and a transverse datum some distance inshore of the proposed ways. The crown of the curve is unlikely to be near the origin of the co-ordinate system. The site will generally suggest initial values. The geometry is shown in **Fig 10**.

For each trial, choose:

Chainage at landward end	c_1	Gradient at landward end	i_1
Chainage at seaward end,	c_2	Chord length between ref block and end of cradle	L_c
Level at landward end,	h_1 (usually +ve)	Angle of build-up of keel blocks	ϕ_b
Level at seaward end,	h_2 (usually -ve)		

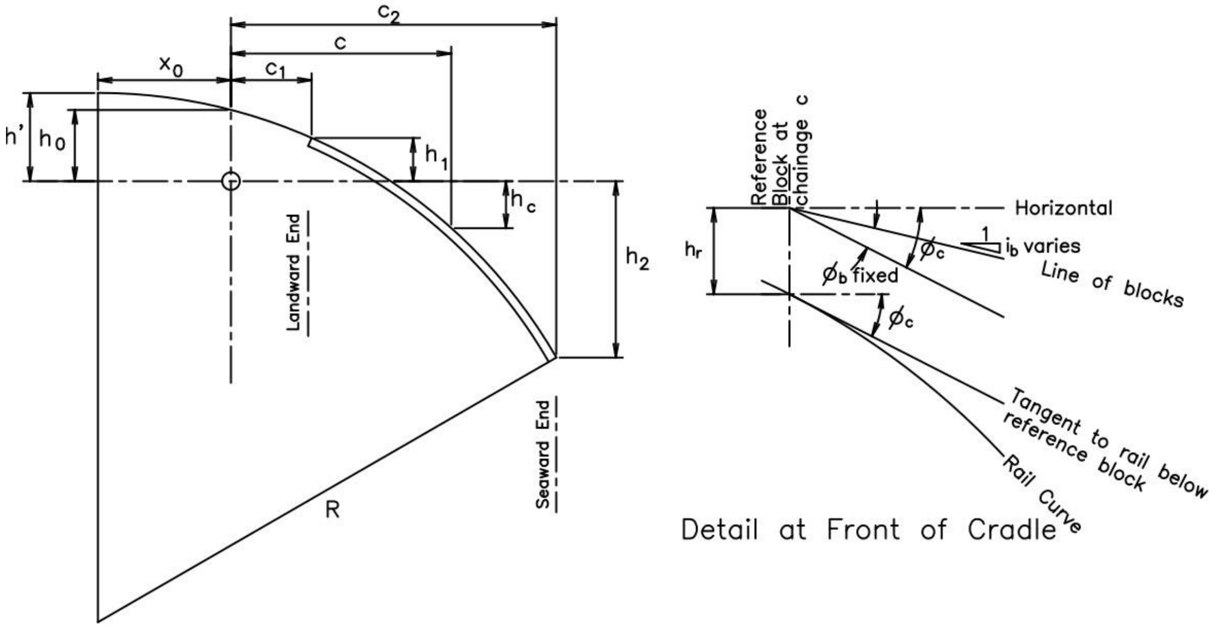


Fig 10: Geometry of Vertically Curved Ways

Now compute the following:

$$\alpha_1 = \tan^{-1} i_1 \qquad (5)$$

$$\alpha_2 = 2.\tan^{-1}\frac{h_1-h_2}{c_1-c_2} - \alpha_1 \qquad (6)$$

Grade of seaward end: $$i_2 = \tan\alpha_2 \qquad (7)$$

Curve radius: $$R = \frac{h_1-h_2}{\cos\alpha_1-\cos\alpha_2} \qquad (8)$$

Crown to origin: $$x_0 = R.\sin\alpha_1 - c_1 \qquad (9)$$

Height of crown: $$h' = h_1 + R.(1-\cos\alpha_1) \qquad (10)$$

For construction, compute:

Level at ch *c:* $$h_c = h' - R(1-\cos\sin^{-1}\frac{x_0+c}{R}) \qquad (11)$$

Arc length ch c_1 to ch c: $$A_c = R\left(\sin^{-1}\frac{x_0+c}{R} - \alpha_1\right) \qquad (12)$$

Gradient at ch *c:* $$i_c = \tan\sin^{-1}\frac{x_0+c}{R} \qquad (13)$$

Chainage at h_c: $$c = R.\sin\cos^{-1}(1-\frac{h'-h_c}{R}) - x_0 \qquad (14)$$

Chainage at i_c: $$c = (R.\sin\cos^{-1} i_c) - x_0 \qquad (15)$$

These equations apply to a reference surface - normally the rolling surface of the rail head. For any other surface, e.g. the underside of the rail flange or, in effect, the surfaces supporting the rail, increase or decrease, as appropriate, the curve radius, *R* by the offset between the two surfaces, normal to the surfaces at any point, and use this revised value, *R'* in *(9)* to *(15)*.

In the case of rails or prefabricated beams supporting the rails, the applicable lengths are the arc lengths given in *(12)* and the relevant surface is the neutral axis of the rail or beam. The radius of curvature of the ways is usually large enough, compared to the section depths that it is unnecessary to pre-form the sections. They will take up the curvature with a minimum of strain.

The trial profiles must be checked against a series of different vessels and of different stages of the tide to ensure that the target vessels can all be got onto the blocks at acceptable stages of the tide.

3.3. Other Curvature

Other vertical curves can be used, notably transitions from a straight grade to a vertical curve but they are only practical on two-point support which, depending on the capacity may involve articulated multi-wheel carriages. This system is particularly applicable to side haul systems where the ways transition from inclined to level.

4. SUING A VESSEL

4.1. The Process of the Sue

The action of suing a vessel is the critical activity in dry docking a ship. It is the action of setting the ship down on the keel blocks. On a slipway it is the action of drawing the vessel up the ways on the cradle as she settles onto the blocks. (The word has the same origin as its legal usage being derived from the Latin meaning *to follow*).

The sue of a vessel begins with the first touch of one or other end of the keel on the keel blocks. The process of the sue is the process of lifting the vessel at this point of first touch, to rotate the vessel longitudinally, to change the apparent trim of the vessel until it is the same as the line of the keel blocks. The keel will then be in contact with the blocks along its full length. In principle, at this instant, the whole reaction between keel and blocks is still at the point of first touch and reaches a maximum value. But immediately, as the vessel continues to be lifted out, the increasing total load is spread out over all the blocks and the point sue load begins to diminish. Once the vessel is high and dry, the sue load disappears and the first touch or sue block only carries its fair share of the total load.

At first touch the marks at the sue end of the vessel will begin to rise out of the water. At the other end of the vessel the marks will, in general, sink into the water by about a third of the amount they rise at the sue end. When the keel touches fore and aft, the marks at the other end will cease to sink and begin to rise out of the water. It is just before and during this period that the vessel must be held in position to locate her correctly on the blocks.

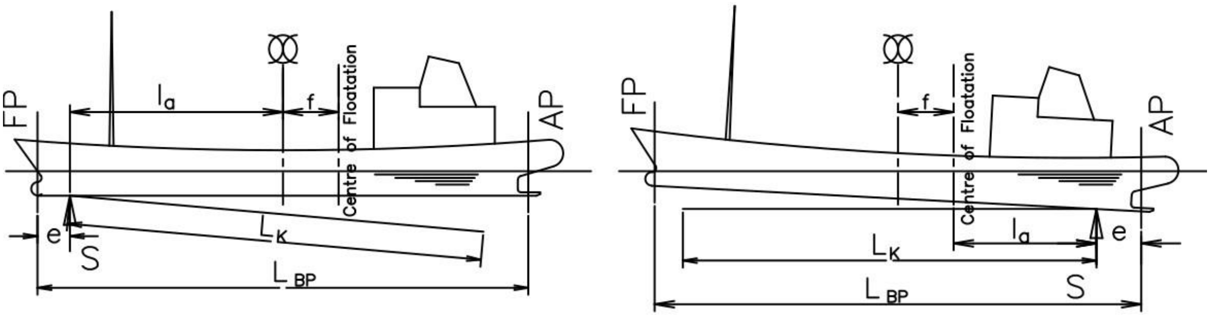
4.2. Sue Loads

The significance of sue loading depends very much on the match between the vessel and the dry docking system.

Where the keel and keel blocks are very nearly parallel the sue loads will be very small and can be ignored. Where there is a large angle between the keel and the line of the keel blocks there will be a heavy sue and the docking of the vessel will be difficult.

4.3. Determination of Sue Load on Straight Grade Ways

Determining the magnitude of the sue load amounts to establishing the upwards force at one end of the keel needed to rotate the vessel longitudinally to change the trim of the vessel to match the slope of the keel blocks. Minikin (Minikin, R.R. 1963) suggests an allowance of between one eighth to one third of the displacement of the vessel. This gives excessive results and better values are needed.



Sue by the Bow

Sue by the Stern

Fig 11: The Sue of a Vessel

The traditional analysis of sue load is given in texts on naval architecture as launching or grounding calculations. To do this, the hydrostatic curves for the vessel are needed. In dry docking design work, these are not normally available.

A first approximation can be obtained by treating the vessel as a rectangular box (ignoring small angle effects at the vertical ends) and analysing the forces involved.

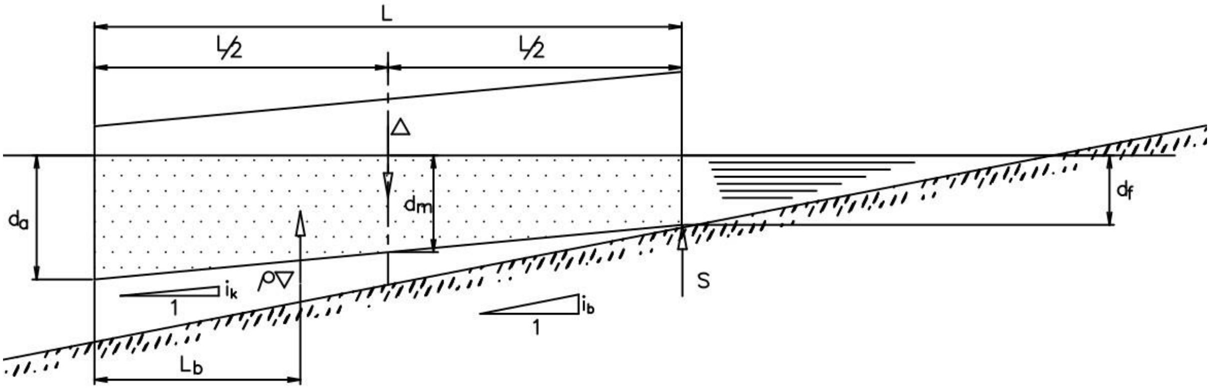


Fig 12: Sue of a Rectangular Box

This analysis of the sue load of the box in **fig 12** gives:

$$S = \frac{1}{6}\Delta\frac{L_{BP}}{d}(i_b - i_k) \tag{16}$$

Although modern ship hull form is approximating more closely to that of a box – i.e. the block coefficient is increasing – a more detailed analysis is needed to take into account the fining of the lines of a real ship. This can be done by approximating all the hydrostatic curves by power functions. Using well-known approximations to typical ship form, the constants to the equations can be approximated by various combinations of block and water plane coefficients.

When the results are evaluated, they are very close to *(16)* and the sue load can be expressed as:

$$S = k.\Delta.\frac{\delta T}{d_m} \tag{17}$$

Where change in trim during the sue, δT is given by:

$$\delta T = L_{BP}(i_b - i_k) \tag{18}$$

and values of *k* are given in **Table 1: Values of k**.

Block Coefficient C_b	**Z – Ratio of Distance of Sue Point to Near Perpendicular tp L_{BP}**						
	0	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**
0.3	0.18	0.19	0.21	0.23	0.26	0.29	0.33
0.4	0.107	0.19	0.21	0.23	0.26	0.30	0.35
0.5	0.17	0.19	0.21	0.23	0.26	0.31	0.37
0.6	0.17	0.18	0.21	0.23	0.27	0.31	0.38
0.7	0.17	0.18	0.20	0.23	0.27	0.32	0.39
0.8	0.17	0.18	0.20	0.23	0.27	0.32	0.4
1.0	0.17	0.19	0.21	0.24	0.28	0.33	0.42

Table 1: Values of *k*

and $$z = \frac{e \pm f}{L_{BP}} \qquad (19)$$

The remaining symbols are as shown in **Fig *8***, **Fig *10*** and **Fig *11***

Draft at Sue Point at Full Sue:

Sue by the bow $$d_s = \frac{\Delta - S}{C_b . L_{BP} . B} - \left(\frac{L_{BP}}{2} - e + f\right) i_b \qquad (20)$$

Sue by the stern $$d_s = \frac{\Delta - S}{C_b . L_{BP} . B} + \left(\frac{L_{BP}}{2} - e - f\right) i_b \qquad (21)$$

The critical points for the sue load are given by:

First touch: $$h_t = t - d_s - h_r \qquad (22)$$

Chainage of first touch: $$c_t = c_1 + \frac{h_1 - h_t}{i_w} \qquad (23)$$

Chainage at full sue $$c_s = c_1 + \frac{h_1 - t + d_s + h_r}{i_w} \qquad (24)$$

Keel Dries when the stern is at:

$$c_d = c_1 + \frac{t - h_r}{i_w} \qquad (25)$$

4.4. Sue on Vertically Curved ways

On vertically curved ways, the grade of the ways is constantly changing during the sue and the analysis becomes much more complex.

Using the same approach of approximating the hydrostatic curves by power functions, the following formulae have been established to compute the magnitude and position of the peak sue load:

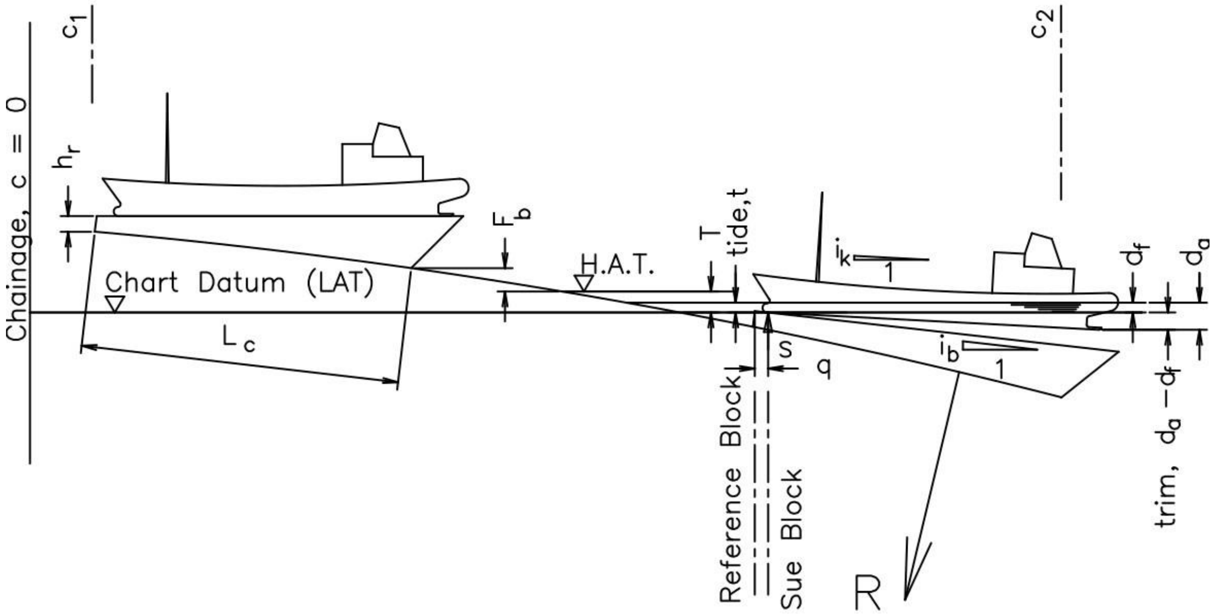


Fig 13: Sue on Vertically Curved Ways

Slope of the keel at full sue $i_s = i_{bs} = \frac{|\sqrt{A^2+B}|-A}{R}$ *(26)*

Sue by the bow $A = R.\varphi_b + q + K.\frac{d_f+d_a}{2} + \frac{1-2.z}{2}.L_{BP}$ *(27)*

Sue by the stern $A = R.\varphi_b + q + K.\frac{d_f+d_a}{2} - \frac{1-2.z}{2}.L_{BP}$ *(28)*

and $B = 2.R\left[h_1 + h_r - t + \frac{d_f+d_a}{2}\left(1 + K.\frac{d_a-d_f}{L_{BP}}\right)\right]$ *(29)*

Block Coefficient C_b	**Z – Ratio of Distance of Sue Point to Near Perpendicular to L_{BP} *(19)***						
	0.00	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**
0.3	0.10	0.11	0.12	0.13	0.15	0.18	0.22
0.4	0.10	0.12	0.13	0.15	0.16	0.20	0.24
0.5	0.11	0.13	0.14	0.16	0.18	0.22	0.23
0.6.	0.12	0.14	0.15	0.18	0.20	0.24	0.29
0.7	0.13	0.15	0.16	0.19	0.22	0.26	0.32
0.8	0.14	0.16	0.18	0.20	0.24	0.28	0.35
0.9	0.15	0.18	0.19	0.22	0.26	0.31	0.38
1.0	0.16	0.19	0.21	0.24	0.28	0.33	0.42

Table 2: Values of K

5. KEEL BLOCK LOADING

Although the quality of the docking plans that are being provided with ships are improving, appropriate docking plans are commonly not available at a slipway design stage. The following procedures will provide an adequate assessment of the loading estimates needed for the structural design of the ways.

5.1. Average Keel Block Loading

Start the process with an assessment of the average keel block loading.

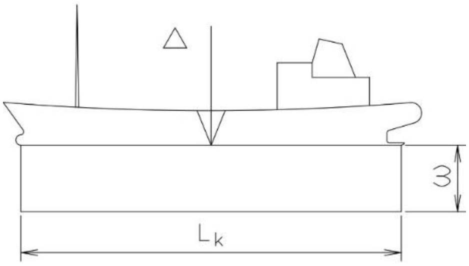


Fig 14: Average Keel Block Loading

$$\omega = \frac{\Delta}{L_k} \tag{30}$$

5.2. Parabolic Loading

In practice the load distribution on the keel is non-uniform and in general tends to an asymmetrical parabolic shape. (McSporran 2000) The position of the peak load will be off centre and its position must be made by estimation.

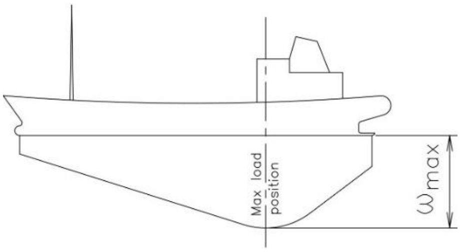


Fig 15: Parabolic Load distribution

The maximum load distribution is given by:

$$\omega_{max} = c.\omega \tag{31}$$

Unless better suggestions are available, use values of c as given in **Table 3: Keel Block Load Factors**

Type of Vessel	Constant c
Very stiff vessels, e.g. submarines	1.5
Stiff vessels e.g. tugs and trawlers	1.6
Medium stiff vessels e.g. freighters and container ships	1.75
Flexible vessels e.g. 'all aft' VLCC's and Cape Bulkers	1.8 – 1.9

Table 3: Keel Block Load Factors

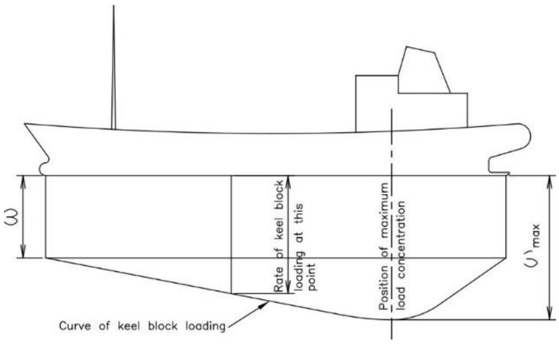
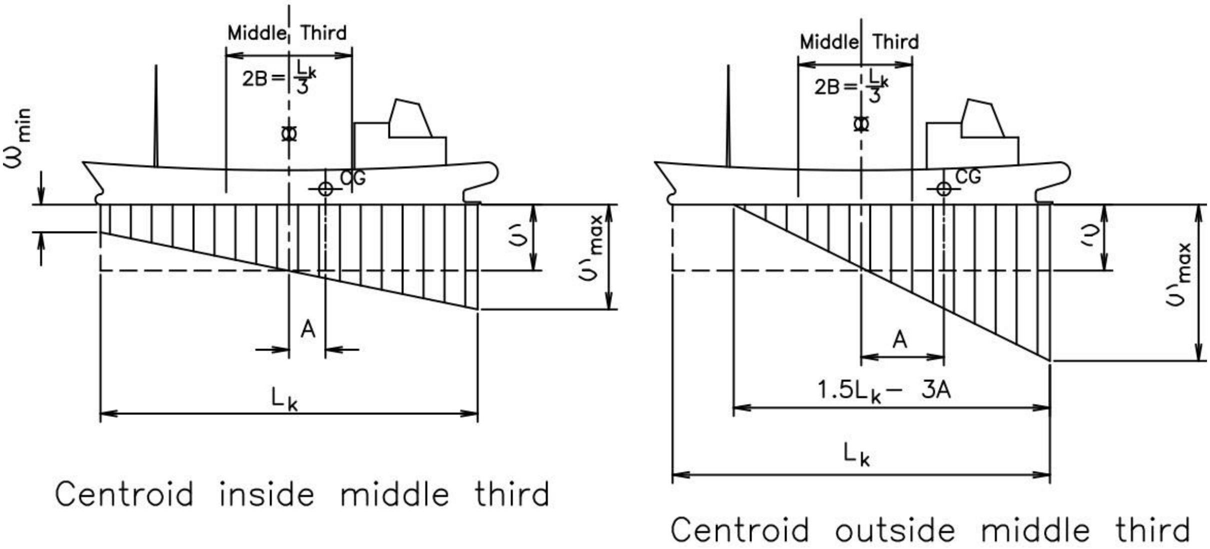


Fig 16: Practical Load Assumption

5.3. Trapezoidal Loading

In general, the substructure of the ways is relatively stiff. With the usual flat, unsprung, cradle the combination will be quite rigid compared to even relatively stiff vessels and the parabolic load distribution as proposed here gives a reasonable load estimate. However, in some cases, particularly when the cradle is built up aft, the system substratum becomes much more flexible relative to stiff vessels. Under these conditions, the asymmetry of the loading becomes pronounced and the load distribution begins to approximate a trapezoidal form (McSporran 2000).

With a trapezoidal load distribution, estimating the position of the peak load intensity is no longer relevant. The key input is the position of the centre of weight of the vessel and whether it is within or without the middle third of the keel (Crandall 1967).



Centroid inside middle third

Centroid outside middle third

Fig 17: Trapezoidal Keel Block Load Distribution

Where the CG falls within the middle third, the minimum and maximum rates of loading are given by:

$$\omega_{min} = \omega\left(1 - \frac{A}{B}\right) \tag{32}$$

$$\omega_{max} = \omega\left(1 + \frac{A}{B}\right) \tag{33}$$

Where the CG falls outside the middle third, the effective length of keel blocks carrying load is given by:

$$L_{keff} = 1.5L_k - 3.A \tag{34}$$

and the maximum rate of keel block loading is given by:

$$\omega_{max} = 2.\omega \tag{35}$$

5.4. Lloyds Rules

Lloyds Rules (Lloyds Register 1981) have been developed for shiplifts but are applicable to slipways. Their load assessments are based on the parabolic method and they define two concepts:

Maximum Distributed Load (**MDL**): this is the maximum safe rate of loading on the keel blocks

Nominal Lifting Capacity (**NLC**): this is the maximum safe total lifting capacity of the cradle/ways system and is given by:

$$NLC = MDL\ x\ L_k\ x\ Distribution\ factor \tag{36}$$

Lloyds allow a maximum distribution factor of 0.83 but normally they will not accept this higher value and limit the distribution factor to a maximum value of 0.67. This is equivalent a minimum value of *c* of 1.5 in **Table 3**.

6. WAYS LOADING – MINIKIN DIAGRAM

Minikin (Minikin R.R. 1963) described a method of plotting the variation of expected peak loading on the ways over the lifetime of the slipway. This is shown in **Fig 15: Minikin's Original Diagram**

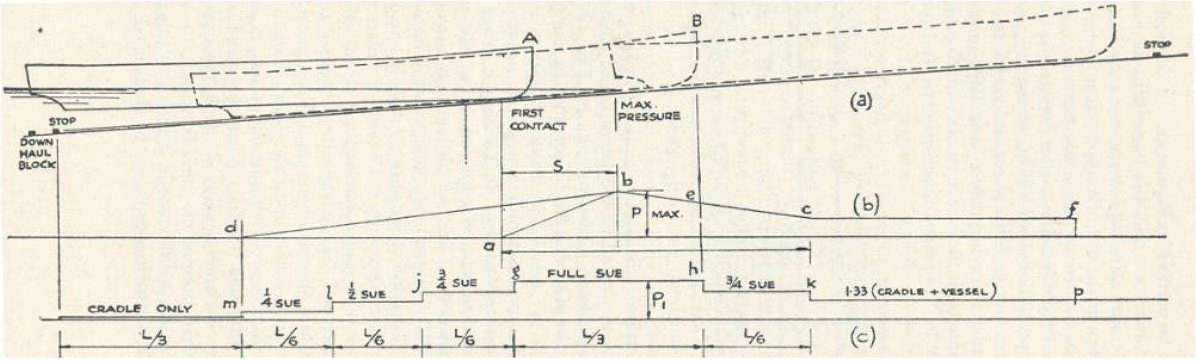


Fig 18: Minikin's Original Diagram

Given the procedures set out above, this diagram must be constructed from a montage of values for different vessels and different stages of the tide.

7. LATERAL SUPPORT FORCES

Ships are normally built symmetrical and balanced about the centreline. In the water they are normally trimmed to float on an even keel without any list to either side. In principle such a ship, dry docked, should balance on its keel without the need of any lateral support. Quite obviously, this would be a most dangerous practice but since the ship is balanced it is not at all clear what forces will be generated in the lateral support system.

Whatever the cause of overturning forces acting on a dry docked ship, they should be treated as overturning moments in order to calculate the forces acting on the support structures.

7.1. Transverse, (Wind) Forces

These occur when the vessel is high and dry and the normal procedures for wind loading on buildings apply. Lloyds (Lloyds Register 1981) propose a horizontal force of 2.5 kN/m^2 or a vertical loading at the outrigger ways or at the bilge suports equal to 20% of the keel loading.

7.2. Vessels with List or Loll

If a vessel is docked on the blocks heeled over at some small angle then it will topple over as it sues unless it is restrained by the lateral support structures – forces that will then be transmitted to the ways structures. As shown in **Fig 16**, the analysis depends on a knowledge of the lever arm l_a and this is difficult to determine. This condition is normally only found in smaller fishing vessels without adequate trimming tanks to bring the vessel back to upright. In general, an allowance of 5° of heel should be sufficient for design purposes.

In practice, vessels liable to cause such problems, will arrive heeled over at some small angle that it is not possible to correct before docking. This situation can be analysed by the principles of hydrostatics irrespective of whether it is the result of list or loll to yield the value of the overturning moment.

The overturning moment is given by:

$$M_t = [(c_1.L_{BP}.B^3) + (c_2.d_m.\Delta)]\tan\emptyset \qquad (37)$$

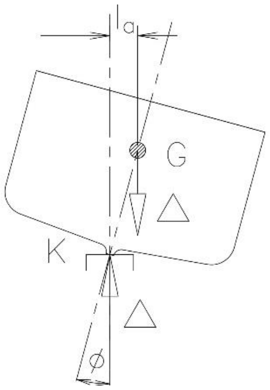


Fig: 19 Overturning Moment

The values of the constants, c_1 and c_2 given in **Table 4: Overturning Moment Factors** have been given in terms of block coefficient although they are actually functions of the waterplane area coefficient, not the block coefficient. However, the block coefficient is usually much easier to obtain than the waterplane area coefficient and appropriate corrections have been made.

Cb	C1	C2
0.4	0.031	0.759
0.5	0.038	0.750
0.6	0.046	0.742
0.7	0.055	0.736
0.8	0.064	0.731
0.9	0.073	0.726
1.0	0.083	0.722

Table 4: Overturning Moment Factors

Equation (*37)* above gives an approximate, not an exact value but one which should be quite adequate for dry docking purposes. ϕ is the angle of heel.

8. WAYS CONSTRUCTION

It is usual and economical to build slipway cradles without any suspension. In this respect they are akin to container cranes. Both require track that is set to extremely accurate levels. For container cranes, on the quayside, in the dry, this is not a difficult matter. Slipway rails underwater are a completely different matter. Extreme accuracy is required from the trade of marine construction underwater that is perhaps the roughest in the construction industry. Some ingenious engineering is required to marry these two.

Generally, a target accuracy better than ±1.5 mm in level and ±3.0 mm in line is adequate. To achieve this, very high accuracy levelling is needed. Where there is a reinforced concrete quay wall or jetty adjacent to the ways, parallax plate and invar staff levelling can be used. A chain of benchmarks will be needed and the highest level of accuracy is needed in surveying these. At this level of accuracy there will be some inconsistency in repeat measurements due to the tidal distortions of the earth’s crust. Where suitable structures are not available some form of water tube levelling will be needed.

A 20 second construction theodolite will generally be sufficient to control the line of the ways.

8.1. Construction in the dry

Construction in the dry reverts to the sort of conventional construction used for container crane rails where it is relatively easy to achieve the required tolerances.

There are parts of the world with extreme tide ranges so that the ways can be constructed in the dry by working at low tide and only taking the ways down to spring low water. This is only really practical for smaller units and dry docking must take place as the tide rises.

Alternatively, the ways can be coffered so that work takes place in the dry. With proper geotechnical design, this is a very effective method but probably not the most economic.

Fig 20: 1200 ton Slipway Construction in the Dry, Port Elizabeth 1945 – Military Specs!

8.2. Prefabricated Construction

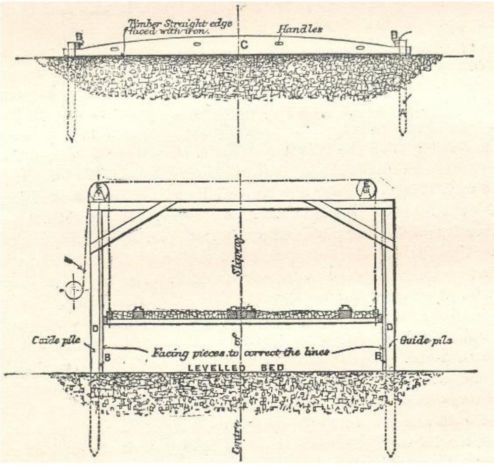


Fig 21: Construction Method for Slipway Ways ca 1895

Brysson Cunningham (Cunningham 1922) describes a method of construction used in 1895 to construct the 1500 ton slipway in East London, South Africa. The ways were still in good condition 100 years later although the facility had been decommissioned some years earlier. In this method, a crushed stone bed was levelled by trammel off prelevelled screed rails. The ways were assembled on pallets of timber and lowered on to the stone bed. See **Fig: 21** (Cunningham 1922).

For the construction of the 1200 ton slipway in Hobart, Tasmania, John Tubb (Tubb J.R. 1970) used load-bearing, prefabricated steel beams in 13 m long sections spanning between piled supports as the ways structure. See **Fig 22** and **Fig 23** (Tubb J.R. 1970) Each section, complete with rail and shuttering for encasing concrete, was template matched on land to the preceding section by means of φ 76 mm (3 inch) pins in 0.8 mm (1/32 inch) clearance holes. The sections fitted precisely without any discontinuity in the top surface between sections. Levelling for this project was done to an accuracy ± 1.5 mm. Accuracy of the final construction was probably somewhat coarser.

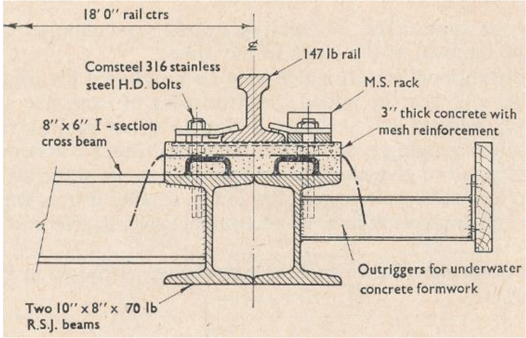


Fig 22: Prefabricated Steel Beam Ways

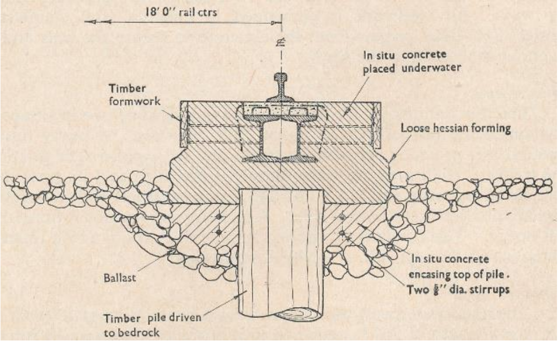


Fig 23: Installation of Steel Ways

Similar methods have been used with precast concrete elements for the ways structure. In general, these are not nearly as effective in meeting the tolerances. In the Saldanha Bay case, there were a number of discontinuities in the order of 25 mm (Mackie, K.P. 1970).

8.3. Incremental Launching

The use of incremental launching of continuously cast concrete ways avoids the problem with joints. This is best done with precast concrete pedestals set to the required level, accuracy and head slope to receive the ways. Rollers can be attached to these pedestals to convey the ways with a 6 mm clearance and then removed when the launching is complete so that the ways settle onto the pedestals. The top of the ways provides the accurate surface for fixing the rails.

For small slipways, ways beams sufficient to carry the load will be light enough to launch over the pedestal rollers and be supported by the pedestals so that no further support is necessary. The only foundation needed is the foundation for the pedestals. For larger slipways a much more substantial structural support must be provided at rough tolerances by conventional construction. The control pedestals can then be set into these supports. The ways beam can be launched over this and encased off it to the required tolerances. In this case the ways beam is fairly insubstantial and serves only to provide an accurate surface for fixing the rails and transferring the loads to the more substantial substructure.

9. ANTI-FRICTION SYSTEMS

9.1. Greased Timber

When ship sleds are used over greased timber the friction is in the order of 10%. Appropriate grease is a heavily graphited No 2 calcium grease i.e. bulldozer track grease.

9.2. Wheels

Very small wheels, generally about φ 200 mm were used on the old patent slipways and they tended to crack like nuts (Tubb J.R. 1970). Friction, particularly with inaccurate track is in the order of 5% to 10%. More recently larger wheels of φ 300 mm to φ 350 mm have been used with the longitudinal members of the cradle steelwork resting on top of the axles. Friction is generally from 2% to 5%. With this arrangement the keel blocks are quite high above the rails necessitating longer ways.

An alternative is to use very large wheels, φ 600 or larger, and hang the longitudinal steelwork below the axles. With this arrangement, there is a significant reduction of the height of the keel blocks above the rails. With these large wheels, friction is < 1%.

It is normal practice to use plain bearings on slipway wheels. Appropriate grease is a No 2 lithium automotive grease or a heavily graphited No 2 calcium grease.

On a 200 ton slipway using the 3-way system, 100 no φ 300 wheels rated at 20 tons would have been needed. Using φ 600 underslung wheels rated at 32 tons on a 2-way system, only 16 no wheels were needed.

Fig 24: φ 600 Underslung Wheel

9.3. Live Rollers

Common practice on railway dry docks is to use live roller trains instead of wheels but they can be used equally on slipways. Friction is commonly < 1%.

Like the wheel, these systems are basically very simple and robust but like the wheel there is a body of specialist knowledge needed to design and maintain them

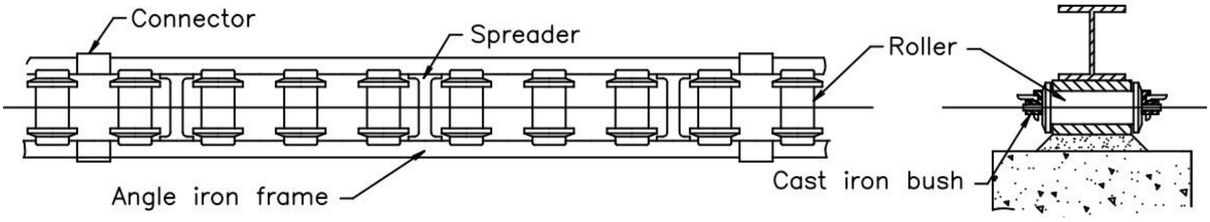


Fig 25: Typical Live Roller Frame

10. Rails

Rails are characterised by the Hertz contact stresses between wheel and rail or between roller and plate. These reach their peak values below the contact surfaces where, even at a safe level, they can exceed the yield stress of the steel and are only safe to the extent that they are contained by the surrounding metal. Steel sections intended for rolling surfaces must have a minimum of section depth – hence the blocky design of a rail head. Provided adequate depth of section is maintained, design of rolling surfaces reverts to the structural issues of support of the load either by shear and bending where the rail spans between supports or by beam on elastic foundation theory where it has continuous support on the ways beam. The former only applies to flat bottom rails with sufficient I value to carry load in bending; the latter to either flat bottomed rails or to roller plates.

10.1. Fastening

Ideally no part of the fastenings should be cast into the concrete. All should be removable and replaceable to simplify rail maintenance. While various standardised, often patented rail clip systems are available, the attachment component is not. Inevitably this involves purpose designed attachments. After the corrosion effects on the rail itself, these are the most maintenance intensive component of system. Unfortunately, the class of person who commonly gets involved in this work, long after the construction has been completed, generally has no concept of the issues involved and lacks the nous to have replicas of the relevant parts fabricated. By and large they all have one knee-jerk reaction: “drill baby drill” and use grouted-in bolts.

The answer is to join them and use properly designed, permanently fixed bolts. For durability these should be of stainless steel. However, the usual grades of 304 or 316 are not adequate. There are a number of more recent alloys that are much more appropriate and a competent stainless steel specialist should be consulted on the alloy selection.

With stainless steel bolts, they may not be allowed to come into contact with the reinforcement. Hence the bolts must be accurately placed. Cast-in bolts are not recommended. The upper surface of the ways beam needs to be steel floated to a fair flat surface and the templates needed to locate the bolts will interfere with the surface finishing. The bolts holes should be drilled into the concrete once it has set using a template to control the drilling. An appropriate proprietary bolt fixing system should be used to set the bolts into the holes in the concrete. The bolts must be set in to the correct depth so that heads of the bolts are at the correct level. Depending on the rail selection and cradle design, high bolts will foul the cradle. This is a common problem with bolts replaced underwater. The heads of the bolts are often set too high and are damaged by the cradle.

With stainless steel bolts it is vital that there is no electrical contact between the bolt and the rail. **Fig 26** is a suggest method of fixing the rails using UHMWPE as spacers and washers to isolate the stainless steel.

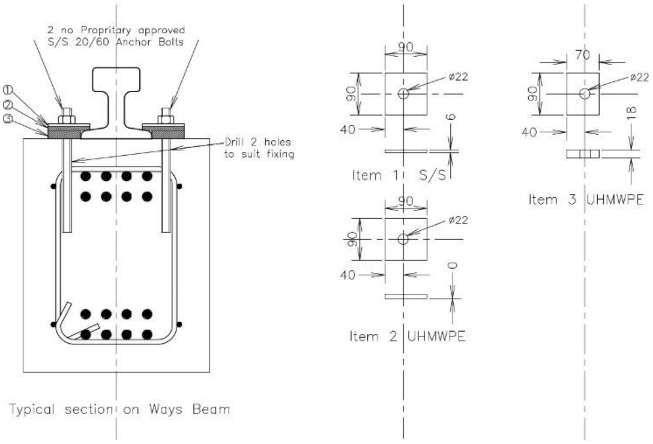


Fig: 26 Suggested Rail Fixing

10.2. Corrosion

Slipway rails exhibit pronounced Accelerated Low Water Corrosion (ALWC) although in the case of these rails, Microbially Induced Corrosion (MIC) does not appear to play any role. Rail corrosion is most intense just below low water springs. On flat bottom rails the weakest part is the thinnest, the web of the rail. With cathodic protection, this corrosion is suppressed below mid tide but becomes severe between mid and high tide. Generally, rails with thickened webs – in the order of 30 mm – should be used and all rails should be given a heavy duty anti corrosion coating.

Flat bottomed rails suffer from two other forms of corrosion, differential aeration cell corrosion and corrugation corrosion both focussed on the tidal zone particularly the lower tidal zone.

The differential aeration cell corrosion occurs in the lower tidal zone and only occurs on the lower end of the upper rail of a pair of rails joined by fishplates and is limited to a short length from the join. There seems to be an electro-chemical couple between the two ends and the head of the upper end of the lower rail is protected and shows no loss of metal. The simple cure is to use full penetration butt welded joins – either copper block welded or thermite welded.

The corrugation corrosion seems to be initiated by pitting corrosion in the rail head. Rolling work hardens the surface of the head outside the pits, changes its electro-chemical potential to more cathodic and sets up a couple between the work hardened metal and the metal in the pit. The effect is exacerbated by the natural frequency of the cradle. Cathodic protection will help.

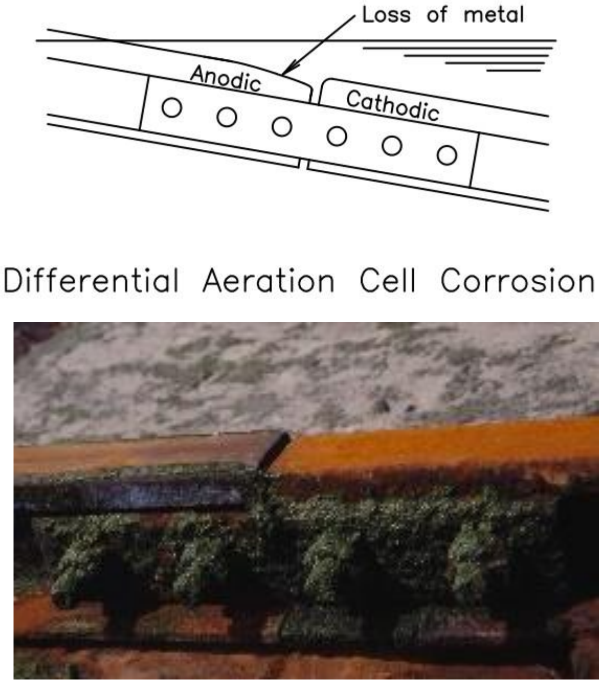


Fig: 27 Differential Aeration Cell Corrosion

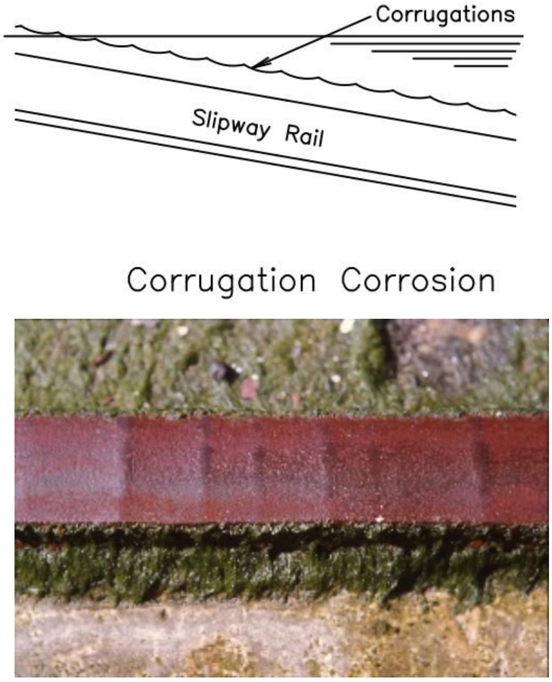


Fig 28 Corrugation Corrosion

The plate rolling surfaces needed for live roller trains seem to exhibit far less corrosion problems than flat bottomed rails.

11. CONCLUSION

The above information, albeit abbreviated, gives a good overview of the complexity of slipway design and should provide a good companion to the design of a slipway and point the way to further investigations.

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APENDIX: Vertically Curved Ways Calculator - Formulae

SHEET 1

Ways Curve Input					Ways Curve Output				
Cell	**Lable**	**Cell**	**Input**	**Description**	**Cell**	**Lable**	**Cell**	**Input**	**Description**
G2	c_1	H2	Input	Chainage at landward end (m)	P2	x’	Q2	=$G4-$F$3	Distance from landward to seaward end (m)
G3	c_2	H3	Input	Chainage at seaward end (m)	P3	y’	Q3	=$G$5-$G$6	Height landward end above seaward end (m)
G4	h_1	H4	Input	Level at landward end (m)	P4	α_1	Q4	=ATAN($G$7)	Slope Angle at land end (rad)
G5	h_2	H5	Input	Level at seaward end (m)	P5	α_2	Q5	=2*(ATAN($X$4/$X$3))-$X$5	Slope Angle at sea end (rad)
G6	i_1	H6	Input	Gradient at landward end (i in1)	P6	i_2	Q6	=TAN($X$6)	Gradient at seaward end (i in 1)
G7	L_c	H7	Input	Chord, ref block to cradle end (m)	P7	R	Q7	=$X$4/((COS($X$5))-(COS($X$6)))	Radius of vertical curve (m)
G8	i_{bb}	H8	Input	Build-up of blocks (i in 1)	P8	x_0	Q8	=($X$8*(SIN($X$5)))-$F$3	Distance from crown to coord origin (m)
G9	δR	H9	Input	Height above or below ref surface (± m)	P9	h’	Q9	=$G$5+$X$8*(1-(COS($X$5)))	Height of crown above datum (m)
G10	T	H10	Input	Maximum tide range (m)	P10	h_r	Q10	=$G$12+$G$13	Block height above rail at reference point (m)
G11	w	H11	Input	Height of shim base above ref surface (m)	P11	R’	Q11	=$X$8+$G$10	Revised radius of vertical curve (m)
G12	b	H12	Input	Height of block above shim base (m)	P12	x'_0	Q12	=($X$12*(SIN($X$5)))-$F$3	Revised distance from crown to coord origin (m)
G13	L_w	H13	Input	Length over keel blocks between block centres (m)	P13	h”	Q13	=$G$5+$X$12*(1-(COS($X$5)))	Revised height of block above rail height at ref (m)

Ways Profile by Arc Length				Ways Profile by Chainage			
Repeat row 19 for further stations at other arc lengths from c_1				Repeat row 19 for further stations at other chainages			
Cell	**Lable**	**Cell**	**Input**	**Cell**	**Lable**	**Cell**	**Input**
B18	A	B19	Input arc length from c_1	J18	c	J19	Input chainage from c_1
C18	c_a	C19	=$X$8*(SIN((A19/$X$8)+$X$5))-$X$9	K18	A_c	K19	=$Y$8*((ASIN(($Y$9+#REF!)/$Y$8))-$Y$5)
D18	h_a	D19	=$X$10-$X$8*(1-COS(ASIN(($X$9+B19)/$X$8)))	L18	h_c	L19	=$Y$10-$Y$8*(1-COS(ASIN(($Y$9+#REF!)/$Y$8)))
E18	i_A	E19	=TAN(ASIN(($X$9+B19)/$X$8))	M18	i_c	M19	=TAN(ASIN(($Y$9+#REF!)/$Y$8))

Vessel Data									
Cell	**Input**	**Cell**	**Lable**	**Description**	**Input Vessel Data**				
Data				**Description**	**Cell**	**Input**	**Cell**	**Input**	**etc**
D34	1	E34	2		F34	3	G34	4	H34=5, I34=6 etc as needed
D35	2	E35	Item		Lable cases - selected design vessels - as needed				
D36	3	E36	$L_{o/a}$	Length overall (m)	Input Cols F, G, H etc as needed				
D37	4	E37	$L_{B/P}$	Length between perpendiculars (m)	do				
D38	5	E38	L_k	Docking length of keel (m)	do				
D39	6	E39	c_b	Block coefficient	do				
D40	7	E40	c_w	Waterplane coefficient	do				
D41	8	E41	Δ	Docking displacement (tons weight)	do				
D42	9	E42	d_f	Draft fore (m)	do				
D43	10	E43	d_a	Draft aft (m)	do				
D44	11	E44	e	Offset of sue point from near perp, fore or aft (m)	do				
D45	12	E45	q	Offse of sue point from cradle reference point	do				
D46	13	E46	h_r	Block height above rail at reference point (m)	All=P10				
D47	14	E47	T	Maximum tide range (m)	All=H10				

APENDIX: Vertically Curved Ways Calculator - Formulae

Sheet 2

Cell	Lable	Cell	Input Data	Cell	Lable	Cell	Computed Data
		B2	3	C4	R	C5	`=Sheet1!$Q$7`
C2	$L_{o/a}$	C3	`=VLOOKUP(3,Sheet1!$D$34:Sheet1!$N$47,$O$5)`	D4	x_0	D5	`=Sheet1!$Q$8`
D2	$L_{B/P}$	D3	`=VLOOKUP(4,Sheet1!$D$34:Sheet1!$N$47,$O$5)`	E4	h’	E5	`=Sheet1!$Q$9`
E2	L_k	E3	`=VLOOKUP(5,Sheet1!$D$34:Sheet1!$N$47,$O$5)`	F4	α_1	F5	`=Sheet1!$Q$4`
F2	L_c	F3	`=Sheet1!$H$7`	G4	α_2	G5	`=Sheet1!$Q$5`
G2	C_b	G3	`=VLOOKUP(6,Sheet1!$D$34:Sheet1!$N$47,$O$5)`	H4	c_1	H5	`=Sheet1!$H$2`
H2	Δ	H3	`=VLOOKUP(8,Sheet1!$D$34:Sheet1!$N$47,$O$5)`	I4	d_m	I5	`=(J3+I3)/2`
I2	d_f	I3	`=VLOOKUP(9,Sheet1!$D$34:Sheet1!$N$47,$O$5)`	J4	i_{bb}	J5	`=Sheet1!$H$8`
J2	d_a	J3	`=VLOOKUP(10,Sheet1!$D$34:Sheet1!$N$47,$O$5)`	K4	h_r	K5	`=Sheet1!$Q$10`
K2	i_k	K3	`=(J3-I3)/D3`	L4	A_b	L5	`=2*$C$5*(ATAN(($F$3)/(2*($C$5+$L$3))))`
L2	w	L3	`=Sheet1!$H$11`	M4	i_f	M5	`=TAN($J$5-ASIN(($F$3/(2*($C$5+$L$3)))))`
M2	b	M3	`=Sheet1!$H$12`	N4	i_a	N5	`=TAN($J$5+ASIN(($F$3/(2*($C$5+$L$3)))))`
N2	T	N3	`=Sheet1!$H$10`			O5	3

Intermediate Parameters				Sue Load Parameters			
Cell	Lable	Cell	Output	Cell	Lable	Cell	Output
C7	δt	C8	Repeat input fraction of tide e.g. 0 to 1 x 0.1 in C8 to C18	C20	δt	C21	Repeat input fraction of tide e.g. 0 to 1 x 0.1 in C21 to C31
D7	t	D8	`=$C8*$N$3`	D20	t	D21	`=D8`
E7	h_{r1f}	E8	`=$D8-$I$3-$K$5`	E20	i_{sf}	E21	`=(ABS(SQRT(($O8^2)-4*$M8*$O8)))/(2*$M8)`
F7	h_{r1a}	F8	`=$D8-$J$3-$K$5-$J$5*$F$3`	F20	i_{sa}	F21	`=(ABS(SQRT(($O8^2)-4*$M8*$P8)))/(2*$M8)`
G7	c_{r1f}	G8	`=($C$5*(SIN(ACOS(1-(($E$5-$E8)/$C$5)))))-$D$5`	G20	n	G21	`=$G$3^(-0.67)`
H7	c_{r1a}	H8	`=($C$5*(SIN(ACOS(1-(($E$5-$F8)/$C$5)))))-$D$5`	H20	h_{da}	H21	`=$D21-$K$5-$J$5*$F$3`
I7	A'_f	I8	`=$C$5*(ASIN(($D$5+$G8)/$C$5))`	I20	c_{da}	I21	`=($C$5*(SIN(ACOS(1-(($E$5-$H21)/$C$5)))))-$D$5`
J7	A'_a	J8	`=$C$5*(ASIN(($D$5+$H8)/$C$5))`	J20	S_f	J21	`=((1+$K8)/2)*($Q8*$H$3*$E$3*($E21-$M$5-$K$3)/$I$5)`
K7	v	K8	`=($L$5-$J8+$I8)/ABS($L$5-$J8+$I8)`	K20	S_a	K21	`=((1-$K8)/2)*($Q8*$H$3*$E$3*($F21-$N$5-$K$3)/$I$5)`
L7	K’	L8	`=1/((12*(3-2*($G$3^(0.33))))+(($G$3^(-0.67))-1))`	L20	A_{r1f}	L21	`=$C$5*((ASIN(($D$5+$G8)/$C$5))-$F$5)`
M7	A	M8	`=$C$5/2`	M20	A_{r1a}	M21	`=$C$5*((ASIN(($D$5+$H8)/$C$5))-$F$5)`
N7	B	N8	`=$C$5*$M$5/2+$L$8*$E$3`	N20	A_{sf}	N21	`=((1+$K8)/2)*($C$5*((ATAN($E21))-$F$5)-$L$5/2)`
O7	C_f	O8	`=$C$5*($M$5^2)/2-$E$5-$K$5-$I$5+$D8-($L8-0.5)*$K$3*$E$3`	O20	A_{sa}	O21	`=((1-$K8)/2)*($C$5*((ATAN($F21))-$F$5)-$L$5/2)`
P7	C_a	P8	`=$C$5*($N$5^2)/2-$E$5-$K$5-$I$5+$D8+($L8-0.5)*$K$3*$E$3`	P20	A_{da}	P21	`=$C$5*((ASIN(($D$5+$I21)/$C$5))-$F$5)`
Q7	K	Q8	`=$L8*$G$3^(-0.67)`	Q20	A_{max}	Q21	`=$P21-$L$5/3`

t = tide (m) i_{sf} = Grade of rail fore at full sue i_{sa} = Grade of rail aft at full sue A_{max} = Arc distance from datum of max load

h_{da} = Height of rail at aft end of cradle when keel dries (m) c_{da} = Chainage of rail at aft end of cradle when keel dries (m)

A_{r1f} = Arc distance from datum to ref point at 1st touch fore (m) A_{r1a} = Arc distance from datum to aft end of cradle at 1st touch aft (m)

A_{sf} = Arc distance from datum to point of full sue fore (m) A_{sa} = Arc distance from datum to point of full sue aft (m)

A_{da} = Arc distance from datum to end of cradle S_f = Full sue fore(t) S_a = Full sue aft (t)