MRCONSULT B.V.

Failure prevention and cost reduction for movable water barriers and bridges with life span guarantee for sliding surfaces

- **sliding guides**
- **sliding seals**
- **plain bearings**
- **bridge plain bearings**
- **gear flanks lubrication**
- **steel cables**

Preview

Main topics:
- Main causes of failure and weakest links
- Choose the design and maintenance variant with the lowest TCO
- Tribology for reducing TCO
- Control of temperature rise by frictional heat, and compression
- Design by omission
- Corrosion types and corrosion prevention
- Material and coating selection for sliding and sealing surfaces, translating
- Material and coating selection for sliding and sealing surfaces, rotating
- Design removable shaft connections
- Failure mechanisms for prestressing bolts and rail tracks
- Failure prevention in open gear transmissions
- Failure prevention through functional monitoring
- Reduce TCO by designing for tension
- Reduce TCO with non-rusting materials
- Reduce TCO with alternative design, material and construction variants
- Reduce TCO with failure prevention checklist
- Calculation examples for time depended temperature rise

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Foreword

On behalf of the government managers are responsible for the operating and maintenance of many structures in a maritime environment, including locks, movable water barriers and bridges with sliding surfaces. Together these form a practical laboratory that has provided us with a wealth of reliable failure knowledge.

This failure knowledge answers the following questions:

- What are the main failure mechanisms for water barriers with sliding sealing surfaces?
- How can these failure mechanisms be quantified?
- Which part of the movable water barrier is the weakest link and determines its availability?
- How can failure mechanisms be controlled or avoided?

The failure knowledge summarized in this document has been built up over more than 40 years and has inspired design and maintenance recommendations for eliminating the most common causes of failure. This knowledge has been updated to date.

Utilization of these recommendations demonstrably leads to control of the availability of these water barriers, and thus to a reduction in the integral costs during design, construction and maintenance, or the Total Cost of Ownership, the TCO. Moreover, this reduces the environmental burden.

This, and my desire to share this expertise is my motivation in documenting it. This knowledge document is rooted in the underlying digital archive in which all design and maintenance aspects are systematically recorded.

I wish you every success in applying this information when offering, designing, building, maintaining and managing, movable water barriers with and without sliding surfaces!

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It's the little things that (not) matter

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Disclaimer
Although this knowledge and experience document was compiled with great care, the author does not assume any liability for damage that might occur through the use of information from this document.

1 Background, introduction and reading guide

1.1 Introduction

Structures are often composed of multiple parts. The unexpected failure of one part - the weakest link - can cause failure of the entire structure. It is therefore important to know weak links in structures in advance and to secure their lifetime in such a way that the required maintenance interval of the structure is achieved. This reduces the costs during the entire life time, also referred to as 'integral costs' or TCO: Total Cost of Ownership.

This paper is mainly concerned with structures with sliding surfaces in and near water, with condensation or in other media. Practical experience shows essentially the following causes of failure in order of decreasing frequency of occurrence:

1. Complexity of composite construction.
2. Material loss due to wear.
3. Crevice corrosion.
4. Glide with too high frictional resistance and/or stickslip[1] .
5. Galvanic and uniform corrosion.
6. Failure of open gear lubrication
7. Fatigue of prestressing bolts.
8. Microbiological corrosion (MIC).
9. Plastic deformation of wheel guides.
10 Ageing of plastics and elastomers.

Figure 1.
A structure is as reliable as its weakest link

It follows that major causes of failure can be prevented with knowledge for it:

1. Simplifying constructions, or 'design by omission'.
2. Managing friction and wear with 'tribo-knowledge'.
3. Preventing corrosion.
4. Control other causes of failure: fatigue, plastic deformation and other causes of failure as collected in the failure prevention checklist in the last chapter of this document.

With the information in this paper weakest links in these structures can be identified. Moreover, the life time of these links can be demonstrably extended and secured so that the availability of the entire construction is extended and secured. This reduces the TCO.

Although this knowledge is inspired by practical problems with movable water barriers with sliding and sealing surfaces in and near water, appears it widely applicable for moving structures with sliding surfaces in and near liquids.

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[1] Stick-slip: a phenomenon that causes uneven movement of a sliding structural element, usually accompanied by noise phenomena related, among other things, to its own vibration frequencies.

1.2 Reading guide

Chapter 1	Starting point: • What are the causes of failure in order of decreasing frequency? • Weakest links determine maintenance interval and TCO • Extend and manage the maintenance interval of weakest links
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Chapter 3	Tribo knowledge for lower TCO
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Annex 3	Derivation temperature formula
Annex 4	f and k of UHMWPE at 20...150 °C
Annex 5	Standard tribo-measurement
Annex 6	Principle shear force in pivot bearings

2 How do I choose the variant with the lowest TCO?

2.1 Maintenance interval as the dial of the TCO

Structures under maintenance tend to stand still. This results in maintenance costs and consequential costs due to production losses or delays in shipping or road traffic. We refer to the sum of maintenance and consequential costs hereafter as 'interval costs'. With each maintenance action, these costs repeat themselves.

The total cost of a structure over its entire useful life is determined by:

- design costs +
- manufacturing costs +
- interval cost times the number of times in the useful life that maintenance is required to prevent failure.

These costs are referred to as 'TCO': Total Cost of Ownership[2], or also by 'integral cost' over the total useful life.

We can reduce TCO by extending the maintenance interval: the number of times interval costs occur due to maintenance will decrease. In other words: *the maintenance interval is an important TCO dial!* Moreover: every maintenance action burdens the environment. It follows that the environmental burden also decreases when the maintenance interval increases.

2.2 How do I choose the variant with the lowest TCO?

During design and maintenance of structures, several variants usually arise that determine the future TCO. How do you calculate the TCO of these variants?

The objective choice of design or maintenance variants is possible as follows:

1. For each design or maintenance variant, calculate the total of the:
   - design costs (if a new construction is involved)
   - building costs (if new construction)
   - future interval costs minus the interest of the future interval costs until the year they are invested (as if the future interval costs were put in the savings bank and earn interest there).

2. The value calculated in this way is called the 'present value' of the design or maintenance variant and is equal to the TCO of that variant.

3. Choose the variant with the lowest TCO.

[2] Costs or revenues related to disposal, reuse and other costs have been excluded for the purpose of this paper.

2.3 Explanation of 'Present Value' (CW) or capitalisation

A future investment is lower than an investment today, even if it involves the same work. Money spent in the future can be put in the savings bank now or used for other investments that generate extra money in the meantime. So capitalising is reducing the future investment by the interest rate of that amount from now until the investment is actually made.

Admittedly, the government or the manager does not put the amount in the savings bank at interest. The manager invests. However, the investment is assumed to yield the same return.

Future costs of variants that are going to be compared should be recapitalised to present as shown below. This recapitalised value is referred to as the Present (or Present) Value (CW): this is the amount that is now (notionally) pledged at, say, *4%* to pay for future costs. This 'discount' (= interest - inflation) is set by the Ministry of Finance.

The CW of a given investment can be calculated as follows:
CW = X / (1+r/100)^N , where:
X = Size of the investment
r = Discount rate, e.g. 4%
N = Anticipated time of investment in Years.

Table 1 *Example calculation CW after10. 25 and 30 years*

Investment [X] (€)	**Discount rate [r] %**	**After [N] (Years)**	**CW (€)**
100 000.-	4	10	67 556.-
100 000.-	4	25	37 512.-
100 000.-	4	50	14 071.-

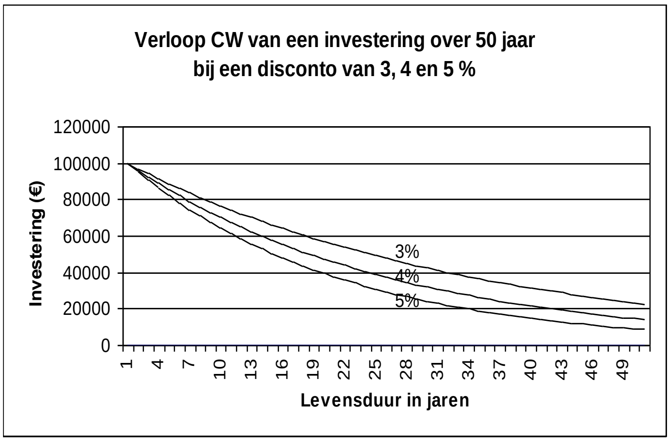

Figure 2. *Evolution of the CW of an investment over 50 years at 3, 4 and 5%*

This example at 3% (top line), 4% (middle line) and 5% (bottom line) shows that the CW of an investment becomes lower the further into the future the investment moment is.

2.4 Choose contract forms that promote failure prevention

Choose contract forms that encourage application of cost-saving techniques [26]. Emphasise TCO - and environmental impact - rather than start-up costs.

As the useful life of the plant is longer - for example, 35 years or more - the owner and operator have a joint interest in applying available cost-saving techniques.

3 Tribo knowledge for lower TCO

3.1 Introduction

In moving structures, fewer components are needed if they are guided by sliding instead of driving. Wheels, rail tracks and point loads are then bypassed. Guidance and sealing then coincide. Recess structures are simplified, see figures 4.1 and 4.2. This reduces mass and production costs and lowers TCO. Chapter 4: 'Design by omission with tribo knowledge' discusses this in more detail.

Translational sliding guiding and sealing of structures involves friction and wear. These can be quantified with the friction coefficients and wear factors in this chapter. In addition, this chapter recommends material combinations that can reduce friction and wear. This information can also be used for choosing material combinations for slide bearings, and for slide surfaces in general.

During sliding, the temperature in the contact between the sliding surfaces increases due to frictional heat. The temperature increases with the sliding times of the construction parts sliding past each other. This temperature increase can be checked with the temperature formula in section 3.6.

Of the recommended material combinations in this chapter, one is always a plastic. The reason for this is that combinations of metals can cause a lot of friction and abrasive wear particles.

Under load, plastics are visco-elastically compressed. This compression can be checked using the compression formula in section 3.7.

Moreover, it is described how environmental factors can influence the friction coefficient and wear factor. This explains that tribo values in practical situations can deviate from the results of tribo measurements in the laboratory.

3.2 Tribological properties

3.2.1 Friction coefficient and wear factor definitions

Tribology is the science and technique employed to control friction and wear. This chapter lists friction coefficients and wear factors of material combinations recommended in practical situations.

3.2.1.1 Coefficient of friction (f)

The coefficient of friction determines the friction between structural parts when it is either to be overcome or desired. The frictional resistance can be calculated by multiplying the normal force on the sliding surface by the coefficient of friction.

3.2.1.2 **Wear factor (k)**

The wear factor determines the rate of abrasion and life time of structural components. The wear (mm) can be calculated by multiplying the wear factor k (mm^2/N) of a material combination by the expected sliding path (mm) and the average surface pressure at that (N/mm^2).

3.2.2 Material preselection

For sliding surfaces, a low coefficient of friction and wear factor are usually desired. To avoid stick slip, it is also desirable that the difference between the static and dynamic coefficient of friction is small to zero. This is the case with PTFE, among others, and with UHMWPE provided the surface roughness *in sliding direction* is low: order 0.5 µm Ra and smaller. Because UHMWPE is hundreds of times more wear-resistant than PTFE, UHMWPE is usually preferred as long as temperature rise and compression are permissible with this material.

- Of UHMWPE based on, for example, GUR 4120 - according to the RWS Requirements sliding loaded plastics RTD 1027.2018 [3] - dozens of coefficients of friction are available with which top values have been calculated by statistics at 90, 95, 99 and 99,9% reliability, see section 3.2.5: 'Top values f of UHMWPE / Sliding surface roughness <0.5 µm Ra'.

- Should there be a preference for a material other than UHMWPE 4120, it is recommended that its coefficient of friction and wear factor be tested against the GUR 4120 variant by means of a representative tribo test - according to Annex 5 - so that comparisons can be made from the top values of UHMWPE calculated by statistics.

If it is calculated that temperature rise and/or compression at UHWMPE are inadmissible, the following alternatives have relatively favourable tribo values:

1. PEEK PVX with a coefficient of friction and wear factor comparable to UHMWPE; disadvantage of PEEK is the very significantly higher volume price.

2. Composite[MR1][3], a fabric-reinforced synthetic resin, possibly mixed with about 5% PTFE or another filler; the volume price is considerably higher than of UHMWPE.
    a. Under comparable conditions and parameters, the coefficient of friction of composite is more than double that of UHMWPE: circa 0,20 or higher [12,13,68].
    b. Under comparable conditions and parameters, the static friction coefficient of composite is higher than the dynamic approximately: 0,25 or higher [12,13,68]; therefore, COMPOSITE can cause stick slip at a relatively low sliding speed and in combination with a critical mass-spring system.

[3] In a (rotating) test setup where the lubricating filler (PTFE or MoS2) of the composite can embed in the roughness valleys of the interacting sliding surface, the measured values of friction coefficient and wear factor are lower compared to the measured values in the practical situation of translating sliding guides. The cause is the loss of lubricating influence of the filling material due to the large relative surface area of the interacting sliding surface in the practical situation compared to the test setup.

c. Under comparable conditions and parameters, the wear factor of COMPOSITE is approximately three times that of UHWMPE: approximately 11*10^-9 mm^2/N [12,13].

3.2.3 Coefficients of friction as an indication

The table below lists coefficients of friction of several materials including PTFE and UHMWPE against steel. The system parameters such as surface pressure, sliding speed and surface roughness in sliding direction at these values are unknown. That’s why these values are only indicative.

Table 2. Indication of coefficients of friction of materials against steel

Aluminium	0,9	Brass	0,5	Steel	0,7
Bronze	0,3	Nylon	0,3	Tin	0,4
Chrome	0,5	Platinum	0,4	UHMWPE	0,1
Diamond	0,1	Polycarbonate	0,2	White metal PB	0,5
Cast iron	0,4	POM	0,2	White metal SN	0,8
Azobé	0,4	PTFE	0,1	Silver	0,4
Copper	0,7	PVC	0,5	Zinc	0,5
Lead	0,8	Rubber	5,0		

Source: Philips CFT.

3.2.4 Tribo values of translating sliding surfaces

Table 3 shows coefficient of friction f and wear factor k of UHMWPE (based on GUR 4120) in combination with harder sliding surfaces; these are sorted by increasing surface roughness in sliding direction.

The data in this table apply in the following situations:

- In water. In dry sliding surfaces, the coefficient of friction is barely higher. This is caused by the low adhesion: UHMWPE repels the water molecules, and thus its lubricating influence. The wear factor for dry sliding surfaces can decrease if the relatively soft wear particles of plastic separate the sliding surfaces from each other and thus act as a lubricant. This phenomenon is referred to below as 'dust lubrication', see section 3.3.7.
- Surface pressure: 2.5 N/mm^2 .
- Sliding speed: 10 mm/s.
- Temperature: < 70° C.
- With higher surface pressure and lower sliding speed, lower coefficients of friction apply, and vice versa; the explanation of this is described in section 3.3.6: 'Influence of parameters and situations on tribo values'.
- The surface roughness *in sliding direction* of the harder sliding surface has more influence on the tribo values than the harder sliding surface material itself.

From dozens of field-tested measurements of the friction coefficient of UHMWPE in combination with a sliding surface roughness in sliding direction of 0.5 μm Ra, average, standard deviation and upper values have been reported at a reliability of 90%, 95% and 99% and 99.9% and at surface pressures from 1…50 Mpa and sliding speeds from 0.01 mm/s to 100 mm/s, see table 4.

Sources for this info are: [14,18,34,60,67,70,91,98,99,103,105].

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