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Wind Loads on Movable Bridges

Effets du vent sur les ponts mobiles

Windlasten auf beweglichen Brücken

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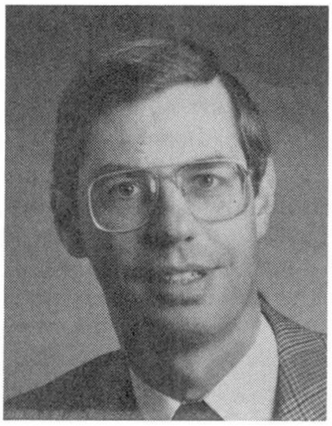

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SUMMARY

This paper examines the question of the maximum wind load at which it is safe to open existing movable bridges. For that purpose a draft procedure has been established for dimensioning the moving gear of bridges for wind load. The fundamental difference between a movable bridge and an ordinary structure had to be analyzed before these principles could be applied. A number of computer simulations were carried out with a stochastic wind load on a bridge deck, enabling the variation coefficient of the response and dynamic amplification factor to be derived.

RESUME

Cet article aborde la question de savoir jusqu'à quel niveau de la charge de vent les ponts mobiles peuvent encore être ouverts. Pour calculer cette charge maximale, on a mis au point une méthode en vue de dimensionner le mécanisme de commande en fonction de la charge due au vent. Pour pouvoir appliquer ces principes, il a fallu analyser les différences fondamentales entre un pont mobile et un pont fixe. Un certain nombre de simulations ont été effectuées par ordinateur pour mesurer la charge aléatoire due au vent exercée sur un tablier de pont, ce qui a permis de déduire le coefficient de variation de la déformation et le coefficient de majoration dynamique.

ZUSAMMENFASSUNG

In diesem Artikel wird der Frage nachgegangen, bis zu welcher Windlast bewegliche Brücken noch geöffnet werden dürfen. Bevor die demnächst erscheinende niederländische Vorschrift angewendet werden konnte, musste zunächst untersucht werden, worin der grundlegende Unterschied zwischen einer beweglichen Brücke und einer festen Konstruktion besteht. Es wurden ausserdem einige Computersimulationen mit stochastischen Windlasten auf den Brückenträgern durchgeführt, woraus der Variationskoeffizient der Verformung und der dynamische Erhöhungsbeiwert abgeleitet wurden.

1. INTRODUCTION

The Public Works Department (= Rijkswaterstaat) designs virtually all traffic bridges on public highways in the Netherlands as well as a large number of other bridges, e.g. over locks. Consequently, the Department is often asked what the maximum wind force is (expressed, for example, on the Beaufort scale) at which a particular bridge can safely be opened. The Regulations for the Design of Movable Bridges (VOBB) are of little use since they only give resulting wind loads. These regulations are currently being revised, and the old VOBB will be replaced by a completely new version based, inter alia, on the EURO-codes and the new Dutch TGB.
These two facts provided sufficient grounds for commissioning a study which was to answer the following two questions:

1. up to what wind velocity can existing bridges still be opened safely, taking into account each specific situation?
2. to what wind load should new bridges, and in particular their moving gear, be calculated to withstand?

2. WIND LOAD ON MOVABLE BRIDGES

2.1. Basic principles

The study of the design values for the wind load on movable bridges made use of the basic principles of the NEN 7600 series (Technical Principles for Building Structures, TGB), which will shortly come into force in the Netherlands. Bridges come under the general heading of "structures" and, in principle, should therefore comply with these standards.
As far as wind loads on bridges are concerned, this means, at any rate, that the principles for determining a design value for the wind load have already been defined. In addition, a number of influences which determine wind velocity have been ascertained. The most important are: height, location (coastal or inland), the ruggedness of the terrain and the way wind fluctuations are described. All that remains is therefore "simply" to establish the distinction between a movable bridge and a fixed structure. For this distinction to be defined properly, however, a number of points first need to be considered.

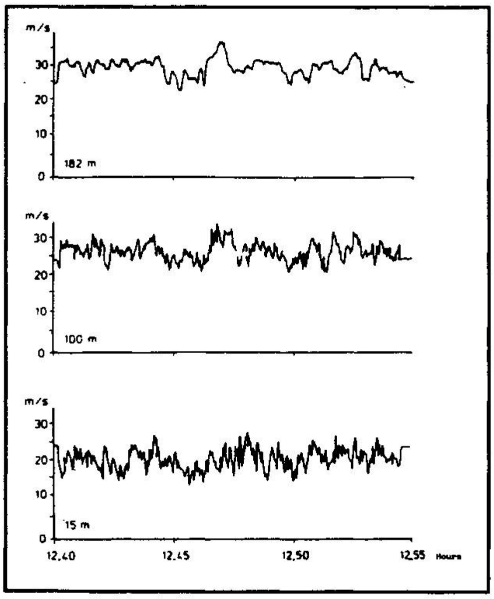

fig.1 Variation in windspeed at 15, 100 and 182m altitude respectively. Watch the decreasing amount of variation, as the altitude increases

The first is fluctuations in wind velocity over time. If wind speed is recorded at a certain point, a pattern is obtained such as in fig.1. From this it can be concluded that it is possible to define wind speed in terms of an average and a variation with respect to the average. Both that average and the deviation (the gust) have a certain probability of occurrence.
Fig.2 shows this for gusts. It indicates that as the velocity in a gust increases, its probability declines. As a consequence, the (design value) of the windspeed is coupled at a certain probability.

In the TGB it was decided to derive the design values for wind load from the extreme hourly average wind velocity in a storm which occurs an average of once every 12.5 years; wind direction is assumed to be random. In the Netherlands the inland and coastal reference velocities thus become 20.5 and 26.0 m/s resp. Within that hour the highest average gust velocity for 3s is accounted for.

The second point to consider is the dimensioning method given in the TGB.
The TGB is based on a so called: "semi-probabilistic" approach. This means that:

- dimensioning is based on a certain probability of reaching a limit state
- the uncertainties in o.a. the load and strength are taken into account by the use of partial safety factors.

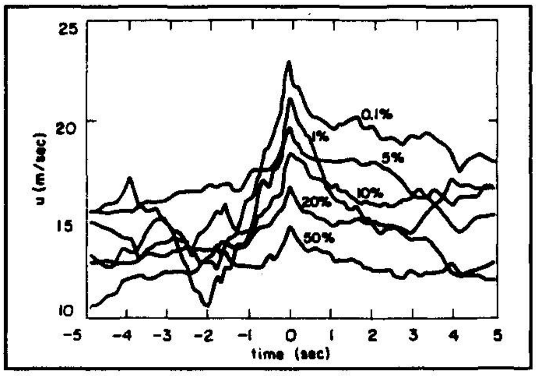

fig.2 Windgusts taken from a population of 1000, with indicated probabilty. As the maximum gustspeed increases, its probability decreases

By judiciously choosing the value of these factors for given levels of uncertainty, the desired probability of attaining a certain limit state can be found or, conversely, the required safety factor for a certain probability can be calculated. It is beyond the scope of this paper to examine exactly how this is done. It is important, however, to know the variation coefficient of the response (e.g. the torque on the motor shaft).

2.2. Numerical simulations

The nature of wind load is such that dynamic effects cannot be ignored. The dynamic response of the structure to a fluctuating load can usually be translated into a dynamic amplification factor. This means that (quasi-)static calculation can be performed. This approach is not always possible for complex problems, and it is necessary to resort to a completely dynamic calculation, the domain being either frequency or time.

Since dynamic influences were expected to have an important impact on the response of the moving gear, it was decided to carry out a dynamic calculation. For this purpose the model shown in fig. 3 was used, which consists of masses and rotational springs. In addition to the usual material damping of 0.7% between the first and second degree of freedom, viscous damping of 10% was applied between the 2nd and 3rd degree of freedom. This causes a damping of 2 to 2.5% for the lowest natural frequency, which closely corresponds to the damping effect of the spring buffer expected on the basis of measurements.

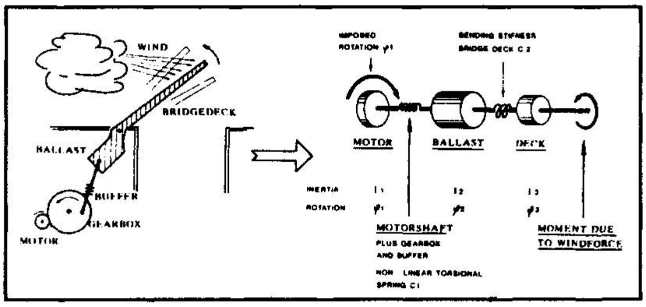

fig.3 Model used to determine the dynamic response of the bridge, as used for the numerical simulations

There is also additional damping, since an efficiency factor of 0.80 has been introduced for the torque transmitted by the gearbox, by applying an opposing torque.

Ideally a calculation in the frequency domain should be carried out, since the response spectrum can then be determined directly. However, in addition to having a favorable (= damping) effect on the response, the buffer also has the awkward effect of producing non-linear system behavior. It has a bi-linear spring characteristic and there is a certain amount of play at the start (fig. 4). It is therefore necessary to resort to a calculation in the time domain and therefore to perform simulations. In addition to wind, also the effects of acceleration and retardation, unbalance, normal braking and an emergency stop were taken into account.

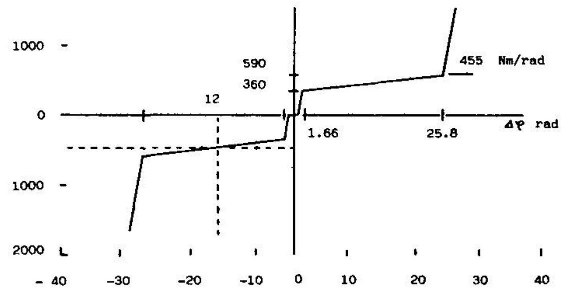

fig.4 Moment-rotation characteristic of C_1 in fig.3

The purpose of the simulations is to determine the response of the system including of the variations resulting from the uncertainties in the load. This therefore means that the variation which may occur in the wind load must be included in the calculation. The calculating of the torque on the motor shaft, for example, is as follows:

1. At a given average hourly wind velocity, wind spectrum and turbulence intensity, one (random) realization of wind velocities is generated.
2. The wind load on the drive mechanism is calculated for these wind velocities, for different opening angles of the fall. This corresponds to proceeding through an opening cycle in small timesteps.
3. For timestep, the response (in this case the torque on the motor shaft) is determined with the dynamic model.
4. The largest torque $M_{(max)}$ from a complete opening cycle is recorded.

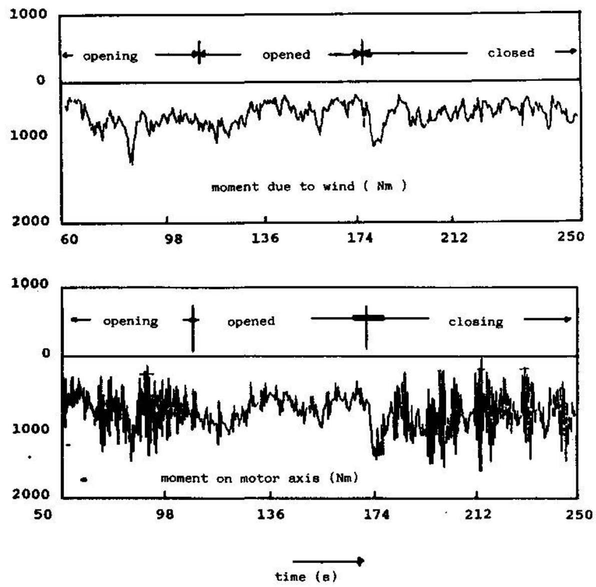

fig.5 Action moment due to wind (upper trace) versus response moment, as a function of time. Watch the dynamic increase of the maximum (torsional) moments.

Fig. 5 shows the wind velocities and the resulting response. To clarify the influence of the dynamic behavior, the wind velocity here has been converted into static action torque on the motor shaft. However, this is a linear transformation and the shape is therefore the same as that of the wind velocity.

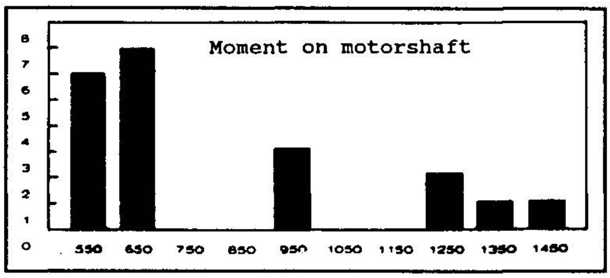

fig.6 Distribution of the torque moments on the motorshaft, obtained from the numerical simulations

By repeating this procedure a large number of times and presenting the results in a histogram, an estimate can be made of the average $\mu M(max)$ and the standard deviation $\sigma M(max)$ of the torque on the motor shaft (see, for example, fig.6). Armed with this knowledge, the partial load factor can be calculated, as indicated in 2.1.

The fact that there is also uncertainty in a number of quantities included in the original calculations as invariant is also taken into account. The figures in table 1 were therefore also used when determining the variation coefficient of (in this case) $M_{(max)}$. Once the variation coefficient of $M_{(max)}$ has been calculated, the required γ-value can be determined.

2.3. The difference between building structures and movable bridges

So far relatively little attention has been devoted to the differences that may exist between a normal building structure and a movable bridge. On the contrary, the basic principles for dimensioning building structures have also been declared applicable to a movable bridge. Nevertheless, it is necessary to examine the similarities and dissimilarities.

symbol	description	distribution	V
P	windpressure hourly average	Gumbel	0,20
C_t	windpressure coeff.	log. norm.	0,12
E	influence of obstacles in the environment	log. norm.	0,11
G	gustfactor	log. norm.	0,16

tabel 1. Overview of parameters used to determine the variation coefficient of the windresponse

When closed, a movable bridge is a "normal" (fixed) structure to which the basic principles of the TGB fully apply. When open, the bridge differs from, say, a building, in three essential respects:

1st The simulations have confirmed that the dynamic properties of the bridge and the moving gear have a significant influence on the response. The dynamic behavior may therefore not be neglected, and must be explicitly accounted for when considering varying loads, such as wind load This is done by applying a dynamic load factor. Guidelines therefore have been deduced for this purpose in the study.

2nd Since a bridge is only open for a limited part of its life, there is less risk of it being hit by a major gust than in the case of a building.

3rd A decision can be made not to expose a bridge to a certain wind load, simply by not opening it.

Point 2 assumes that there is an unlimited opening regime.
In principle, the bridge may be opened at any time, but the duration of the opening cycle may be so short that the chance of the maximum gust occurring in that period is thereby reduced. This is expressed in a reduction factor Ψ, applied to the design windspeed. In the case of an average opening duration of 3 minutes per hour, i.e. for 5% of the time, the factor is at least $\Psi = 0.8$.

In the case of point 3, there is a limited opening regime; i.e. if a particular wind force is forecast (e.g. Beaufort 9), the bridge is not opened as long as the warning lasts. The bridge will therefore be exposed to a lower average wind force than in the case of an unlimited opening regime. If the wind force is limited to below Beaufort 9, for example, the average wind velocity can be reduced by a factor of 0.70.

APPLICATIONS

3.1. Guidelines for new bridges

The work described above has resulted in a proposal for guidelines for the wind

load on movable bridges. The guidelines discuss a number of additional matters which could not be dealt with in the scope of this paper, such as: method of calculation to be used, shape factors and windspeeds to be used in case of a reduced opening regime.
The following limit states are distinguished in the proposal:

A. Failure of the transmission, or parts of it
B. Insufficient motor power, resulting from:
   - the exceeding of the average power available
   - the exceeding of the maximum power available (heat balance of motor)
C. Insufficient braking power

It is indicated which load combinations must be examined, which γ_W- and Ψ-factors must be used and how the dynamic load factor can be determined. A distinction is also made between an unregulated motor (for which the torque-speed curve is fixed by is vary nature) and a regulated motor, whose speed is controlled electronically.

As an example, the limit state for exceeding the maximum braking torque, in the case of an opened bridge is given below.

$M_{brake} \geq \gamma_{wind}\, \phi_{wind}\, M_{wind} + M_{unbalance}$, where:

M_{wind} = wind moment, calculated with the wind pressure according to the TGB and reduced by a factor ψ = 0,8
ϕ_{wind} = dynamic load factor, calculated according to the proposed guidelines
γ_{wind} = partial load factor for wind, in this combination = 1,1

3.2. Permissible wind load on existing bridges

Although this is the last subject to be discussed, it was the point of departure for the study. The very question to be answered was the maximum wind velocity at which a number of bridges over locks in the province of Zeeland might still be opened.
The results obtained allow this question now to be answered. It is necessary, of course, to take account of the actual situation regarding a particular bridge in terms of the strength of the moving gear, the maximum motor torque available and the braking torque to be applied.

As at the time of writing this paper, this job has not been completed, only an indication of the results can be given here.
It looks as if in the moseyed interesting case (that is the most important bridge), the magnitude of the braking torque is the decisive parameter. If it is too small, the bridge could be blown shut; if it is too high, the moving gear may become overloaded as a result of an emergency stop. Fortunately, however, the braking torque can be adjusted, so that the optimum value can be set. This leads to a maximum permissible reference wind most of 14 m/s. This value might be increased if the reliability with which its occurrence can be predicted is increased. In cooperation with the Royal Netherlands Meteorological Institute (KNMI) studies are being conducted of the extent to which an advanced wind-measuring system at the site of the bridge might contribute to this.

ACKNOWLEDGEMENT

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