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# THE WAY TO A FLOODRISK-BASED SAFETY CONCEPT
# FOUR CASE STUDIES

Discussion paper transmitted by the Government of the Netherlands */

(Prepared by Messrs. A.M. VAN AGTHOVEN, F. DEN HEIJER and A.W. KRAAK)

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**SUMMARY**

The Ministry of Transport, Public Works and Water Management is considering to enhance its flood protection policy. In the future a flooding risk concept is foreseen, in which both flooding probabilities and the consequences are taken into account. To calibrate the new safety concept 8 case studies for different polders in the Netherlands will be made. A clear reference point must be set. In the case studies traditional and current design rules are compared with a provisional definition of the reference point. Besides a model to calculate the flooding probability of a polder was developed to investigate the consequences of the reference point in terms of flooding probabilities. The tentative results of 4 case studies lead to the conclusions that the provisional definition of the reference point gives results that do not deviate much from former methods and that a level II system approach to calculate flooding probabilities is possible.

## 1. INTRODUCTION

The present safety standards of the Dutch dikes and other flood defences are expressed as frequencies of waterlevels and associated wave impact that every dike section must be able to resist. These safety standards were set by the Delta Committee after the flood of 1953 in the South-west of the Netherlands. The Netherlands were divided in more than 50 smaller areas, called polders or dike ring areas. Four classes of dike ring areas can be distinguished in terms of water level frequencies: 1/1250, 1/2000, 1/4000 and 1/10000 per year, depending on the consequences of flooding.
The Ministry of Transport, Public Works and Water Management is considering to enhance its flood protection policy. In future a flooding risk concept is foreseen, in which both flooding probabilities and the consequences of flooding are taken into account.
In the present Dutch flood protection law an evolution from waterlevel criteria towards probability of flooding has already been included. The question is when and how the transition to flooding probabilities can be made.
The transition from waterlevel criteria towards flooding probabilities is not meant to change the current safety level. On the contrary: the current safety level seems to be generally accepted and should be maintained. The mentioned transition is firstly meant to get a clear unit to compare flooding risks with other social risks.
To start the transition to flooding probabilities a so-called "reference point" has to be defined to give clear insight in the current safety standards. Then the new safety philosophy can be related to this reference point.

The reference point can not easily be deduced from history, because safety philosophy and design rules were often changed and vary for different areas, constructions or failure mechanisms. The Delta Committee developed a clear safety philosophy, but probabilistic techniques and knowledge of failure mechanisms were not sufficient to work out design rules strictly to this philosophy. So the current Dutch guidelines for design of dikes and other flood defences are not completely consistent and explicit in safety philosophy. Therefore, in defining the reference point, a choice had to be made to set the state of the art of flood protection. In 1993 a concept for the reference point was made. The main constraints were that

- every single dike section should satisfy the safety standards according to the philosophy of the Delta Committee;
- the latest, accepted knowledge should be applied;
- no major changes in required dike geometry compared to present insight will be accepted.

However, the consequences and the practical value of these rules were not yet clear. This led to the idea to carry out 8 case studies for 8 different polders in the Netherlands. In addition the case studies are used to set up a first concept for the calculation of flooding probabilities.

In this paper the goals, the tentative definition of the reference point, the methodology and the first results of these case studies will be treated.

## 2. GOALS

The first goal of the case studies is to compare "traditional" dike design, design according to the latest guidelines and design according to the reference point, in order to get a clear picture of the consequences of the reference point related to historical development in design rules.

The second goal is to estimate the flooding probabilities for the entire polder. Because the future safety standards will be based on flooding probabilities, the consequences of the reference point in terms of flooding probabilities must be paid attention to. With this aspect the case studies are not only a stock-taking of the state of the art, but also important new tools for the future safety philosophy are developed.

Both goals support the final goal to get a clear reference point to calibrate the future new safety philosophy.

## 3. REFERENCE POINT

The reference point is a number of design rules with a safety philosophy according to the Delta Committee. The safety philosophy of the Delta Committee is that every dike section should be able to withstand the design waterlevel safely. Because absolute safety can never be guaranteed this is translated as the failure probability at design circumstances should be "small", which is between 0.1 and 0.01.
The first requirement to resist the design waterlevel is that the dike should be high enough. Because in general extreme waterlevels are accompanied by wind waves, wave overtopping is the pimary failure mechanism.

The design rules of the reference point consist of two parts: a model to describe a failure mechanism and a safety criterium. Model descriptions for the main failure mechanisms

are available, but safety criteria are inconsistent or not explicitly explained. So for the reference point a decision must be made about these criteria. The safety criteria should meet the following conditions:

1. the probability that the acceptable overtopping is exceeded should be smaller than the waterlevel frequency from the flood protection law;
2. the probability of flooding if the acceptable overtopping is exceeded should be small;
3. the probability of flooding by other failure mechanisms should be small with respect to the probability mentioned above.

In formulas

$$P(q>q_{acceptable}) < legal\ standard \quad (1)$$

$$P(failure|q>q_{acceptable}) < p \quad (2)$$

$$P(failure\ by\ other\ mechanisms) < \xi \cdot N \cdot legal\ standard \quad (3)$$

in which $\xi$ and p are small (0.01-0.1) and N depends on the failure mechanism. If the probability of a failure mechanism is independent every year N=1, if the probability between different years are correlated N>1.

p and $\xi$ must be chosen in such a way that

- the probability of flooding by exceeding of the design waterlevel for all failure mechanisms together should be small;
- changes in dike geometry in relation to the currently used design rules are as little as possible.

## 4. METHODOLOGY OF THE CASE STUDIES

The case studies are carried out for simplified situations in the Netherlands. Geographically they are chosen in such a way that all different physical systems are involved. The real polder is schematised to a limited number of sections, so that all essentially different types and different orientations of the flood defences are represented.

The most important failure mechanisms are taken into account:

- overtopping (water is running over the dikecrest)
- piping (seepage water erodes the dike internally)
- sliding (instability of the inner- or outerslope)
- erosion of revetments followed by erosion of the core material
- dune failure
- failure of sluices or other constructions

According to the reference point the newest formulas for the description of the failure mechanisms should be used. The chosen model descriptions and the current safety criteria are given in table 1.

*Table 1 Design rules for failure mechanisms*

| Failure mechanism | Model for reference point | Current safety criterium |
|---|---|---|
| Overtopping | Van der Meer (1993) | $P(q>q_{acceptable})$ < legal safety level |
| Piping | Sellmeijer (1994) | safety factor |
| Sliding | Bishop, Guideline Riverdikes (1985) | safety factor |
| Erosion of revetments and core material | Guideline for Safety Assessment (1997) | $P(H_s>H_{design})$ < legal safety level |
| Dune erosion | Guideline Dunes (1984) | P(dune < critical geometry) < legal safety level/10 |
| Failure of sluices or other constructions | Guideline Constructions (1995) | - $P(q>q_{acceptable})$ < legal safety level<br>- P(failure at closure) < legal safety level/10<br>- P(instability) < legal safety level/100 |

In the first part of the case studies three design methods are compared:
- "traditional" design
- design according to the latest guidelines
- design according to the reference point

"Traditional" design is the methodology as practised before the release of the latest guidelines. A pragmatic approach is necessary because development of techniques and the practical application is a continuous process. The reason for the interest in traditional design methods is to get more insight in the accepted changes in the past.

The second aspect of the case studies is the calculation of flooding probabilities. With a level II system approach a rough estimation of the flooding probability for the entire polder is made. In the system analysis all above mentioned failure mechanisms are taken into account. In the following paragraph the system approach will be treated thoroughly.

## 5. SYSTEM APPROACH TO THE SAFETY OF A POLDER

### Introduction

In the present safety standards the design criteria are defined per individual dike section. A dike section is defined as a stretch of dike with more or less constant values for characteristic load and strength variables. One dike section is in general a few hundreds meter long, depending on for instance the orientation of the section, the geotechnical and geometrical features of the dike cross sections. This means that the safety of a number of dike sections is lower than the safety level of an individual section. A chain with many hinges is less strong than a chain with only a few of the same hinges. Moreover a dike ring area which is exposed to high water levels from the sea on one side and high water levels from the rivers on the other side has at least a probability of failure which is twice

as high as the probability of failure of one side, because of the fact that storm surges and high river discharges are independent events. So the dike ring area should be considered as a system of individual components, and thus be analyzed as a system [1].

**Reliability functions**

Often as a result of extensive research a reliability function can be defined for each failure mechanism. In general such a reliability function Z is a function of the load or stress variables and variables representing the strength or resistance. In general format

$$Z = Z(X_1, X_2 .. X_n) \qquad (4)$$

with Z(..) the reliability function and $X_i$ a stochastic variable.

Z is defined in such a way that Z < 0 corresponds to failure of the dike section. If R is a function of the resistance variables and S a function of the stress variables then Z can be put in the format:

$$Z = R - S \qquad (5)$$

If R and S are described statistically in terms of a probability density function, then the area in which Z < 0, corresponds to the failure probability of the mechanism considered. For the assessment of this probability of failure several techniques are available such as First Order Reliability Methods (FORM), Monte Carlo simulation techniques and Numerical Integration.

By applying FORM the failure probability is given by

$$P_f = P(Z < 0) = \Phi(-\beta) \qquad (6)$$

in which $\beta = \mu_Z/\sigma_Z$ = reliability index and $\Phi$ is the normal distribution function.
$\Phi(-\beta)$ can be approximated by $\Phi(-\beta) \approx 10^{-\beta}$ for $1<\beta<4$.
Another important result of FORM is the influence coefficient $\alpha_k$ ($0<\alpha<1$), which shows the relative contribution of the variable $x_k$ to the failure probability.

From cross section to dike section

For each cross section of the dike and each failure mechanism a reliability function is available with stochastic variables representing the strength and loads on the flood defence. In general such a reliability function is valid for a certain length of the dike. This length is limited due to the effect that variables loose their correlation further away from its original cross section. For instance the height of a dike in one cross section is correlated to the height 20 meters next to it, but is hardly correlated to the height of the dike 10 kilometres further. In contrast to for instance the waterlevel in front of the dike which probably has a strong correlation over kilometres of length. This effect of correlation is called the length-effect. The same principle is not only valid in space but in time as well.

So for each variable the following statistical features have to be defined, per mechanism and cross section:

- type of the probability density function
- a mean value
- a standard deviation
- a correlation function in the space domain x
- a correlation function in the time domain t

All features should be based on a combination of field measurements, laboratory experiments and model results. The correlation function is in general composed of a constant correlation $\rho_x$ or $\rho_t$ and a term which is a function of x or t and decreases to zero in space or time. So for the spatial correlation:

$$\rho(r) = \rho_x + (1-\rho_x)\exp[-(r/d)^2] \tag{7}$$

in which
- $\rho_x$ = constant correlation
- d = correlation distance
- r = distance between two cross sections

For operational reasons this function is represented as a Ferry Borges Castanheta model with intervals $\Delta=(d_x\sqrt{\pi})/\beta$ (approximation for $\beta>2$), in which $\beta$ is the reliability index of the individual cross section. Within the intervals the correlation is full and between the intervals the correlation is constant.
In case of a number of stochastic variables with different correlation distance then a representative correlation and correlation distance must be calculated

$$\rho_x = \sum_k \alpha_k^2 \rho_k \qquad (\frac{1}{d})^2 = \sum_k \frac{(1-\rho_k)}{1-\rho_x}(\frac{\alpha_k}{d_k})^2 \tag{8}$$

with k the index for the stochastic variable.

The reliability of the cross section, $\beta$, has to be calculated before the length-effect can be counted for. Then, the reliability index for a dikesection can be calculated with

$$\beta_{dike\ section} = \beta_{crosssection} - \log(\frac{L\beta_{crosssection}}{d\sqrt{\pi}})\sqrt{1-\rho_x} \tag{9}$$

with L the length of the dikesection.
For the time domain correlation similar procedures are applied.

From dike sections to a system of dike sections
After the analysis for every single dikesection or element, the reliability of the system must be calculated.
Consider a series system of n elements. The probability of failure is

$$P_f = P(Z_1<0 \vee Z_2<0 \vee \ldots Z_n<0) \tag{10}$$

First the Cornell-bounds are investigated showing that the failure probability of the system is per definition larger than the weakest element, but smaller than the sum of the failure probabilities of the elements. If one of the elements has a failure probability which is an order of magnitude larger than the other elements, then the bounds are more or less the same. If this is not the case then a procedure has to be followed in which the failure probabilities of the elements are combined:

Consider two elements $Z_i$ and $Z_j$. Knowing the individual reliability indices and the correlation between $Z_i$ and $Z_j$, the probability $P(Z_i<0 \vee Z_j<0)$ can be calculated (method Hohenbichler). $P(Z_i<0 \vee Z_j<0)$ can be replaced by an equivalent reliability function $Z_e$ such that $P(Z_e<0) = P(Z_i<0 \vee Z_j<0)$, with related reliability index $\beta_e$ and approximated influence coefficients $\alpha_{ek}$ (figure 1).

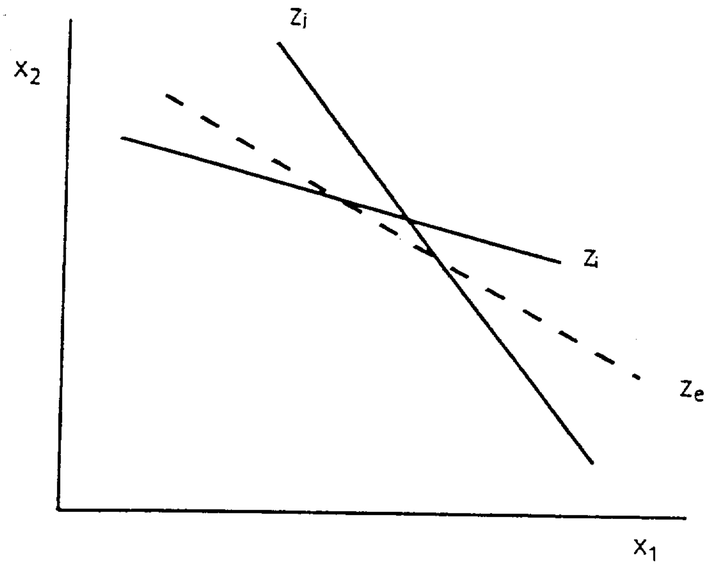


*Figure 1 The combination of two Z-functions to an equivalent Z-function*

The original set of n Z-functions is reduced to a new set of (n-1) Z-functions. Repeating this procedure eventually leads to the overall probability of the system. Best results are obtained by combining in every step the two best correlated reliability functions. An example for 4 elements is shown in figure 2.

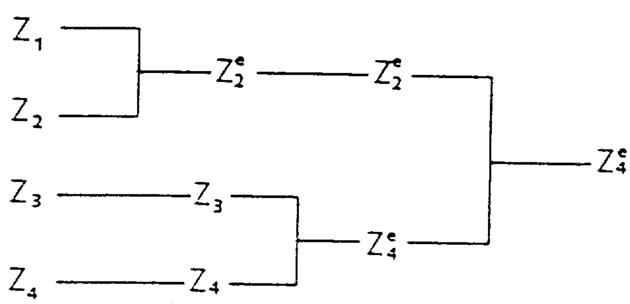


*Figure 2 Scheme for the calculation of the systems reliability by equivalent Z-functions.*

## 6. RESULTS AND INTERPRETATION

Here some of the tentative results of 4 case studies, Waarderlanden [2], Lingerwaard [3], Grofriland [4] and Kabeljauwsche Waard [5] are presented (figure 3). The names are fictive, because of the simplified schematisation.

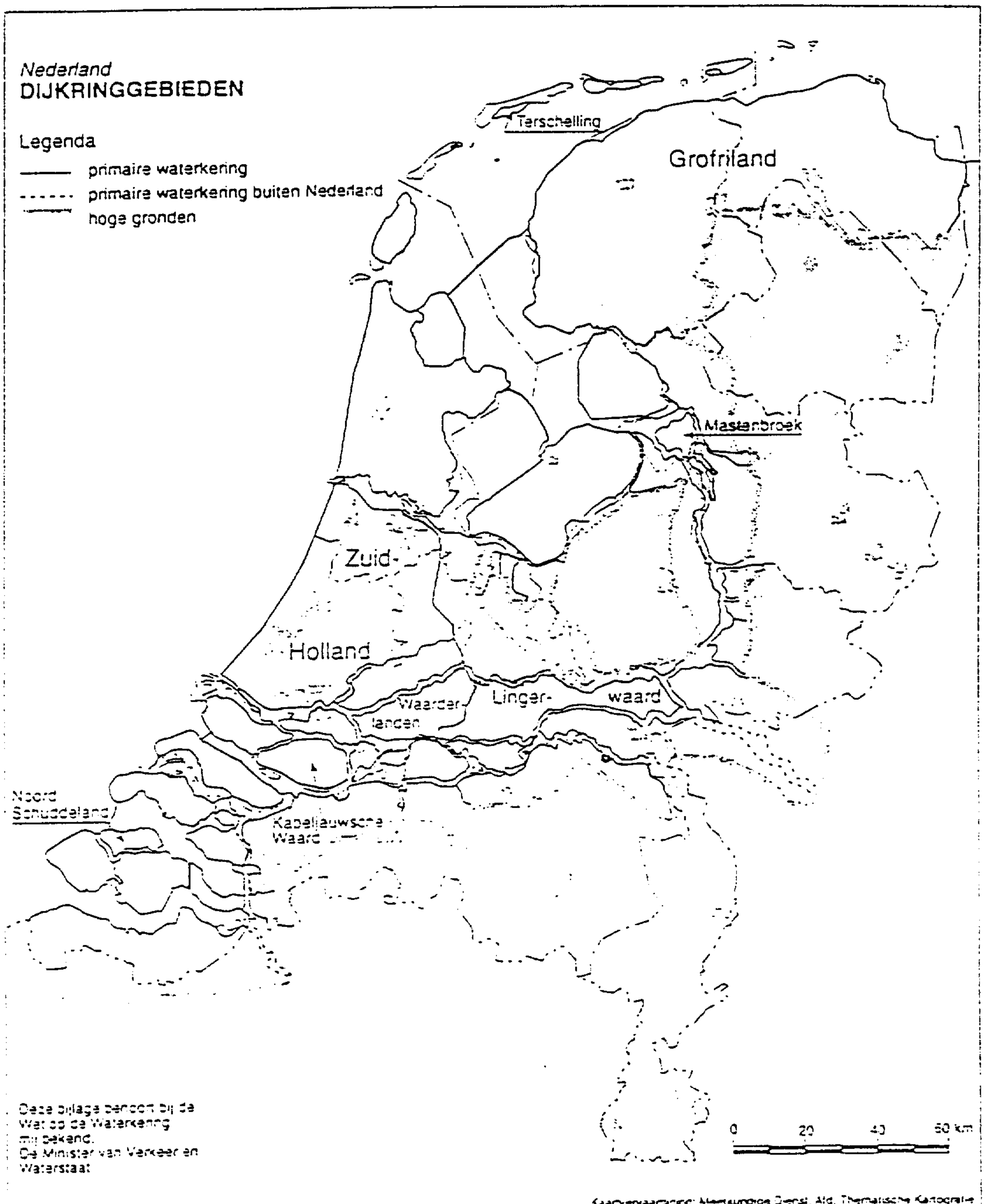


*Figure 3 The Netherlands with the case study areas*

In the case studies the system approach of section 5 has been applied, leading to the reliability per mechanism, the reliability per section and the overall reliability. A reliability function was available for all mechanisms. However the estimation of the statistical values of each variable was not aimed by this study, so best guess approaches were used in case no information was available.

In table 2 the reliability indices for the case study Waarderlanden are given for some of the analyzed dikesections.

*Table 2 Reliability indices for the case study Waarderlanden*

| dikesection | L [km] | overtopping | piping | sliding | failure of revetments | total |
|---|---|---|---|---|---|---|
| Hardinxv g o | 2.0 | 4.0 | 5.6 | 5.5 | 5.1 | 4.0 |
| Nieuwlek w | 1.0 | 4.9 | 9.8 | 5.8 | 6.9 | 4.9 |
| Langerak 258 | 1.0 | 5.3 | 4.6 | >6 | 3.6 | 3.6 |
| Langerak 226 | 2.0 | 5.1 | 4.7 | >6 | 5.3 | 4.7 |
| ring | | 3.8 | 4.5 | 4.3 | 3.6 | 3.4 |

In table 3 the preliminary overall reliabilities for 3 case studies are given.

*Table 3 Overall reliabilities*

| | ß | Most contributing failure mechanism |
|---|---|---|
| Waarderlanden | 3.4 | erosion revetments and closure of barriers (both ß=3.6) |
| Lingerwaard | 2.6 | erosion revetments (ß=2.8) |
| Grofiland | 2.4 | overtopping (ß=2.5) |

For two of the case studies the calculated flooding probabilities are large and probably not realistic. This can be explained by the fact that it is not yet possible to give good criteria for failure. For most failure mechanisms the models describe the beginning of failure, which does not necessarily mean that a breach is formed and the polder is getting inundated. Only if the extreme loads continue long enough, beginning of failure will eventually lead to flooding.

In figure 4 the freeboard averaged for the entire dike ring is given for the traditional design method, current design method and the method according to the reference point with p=0.1 and p=0.01. Figure 4 shows that if p is chosen somewhere between 0.1 and 0.01 the reference point does not give major changes compared with former design rules.

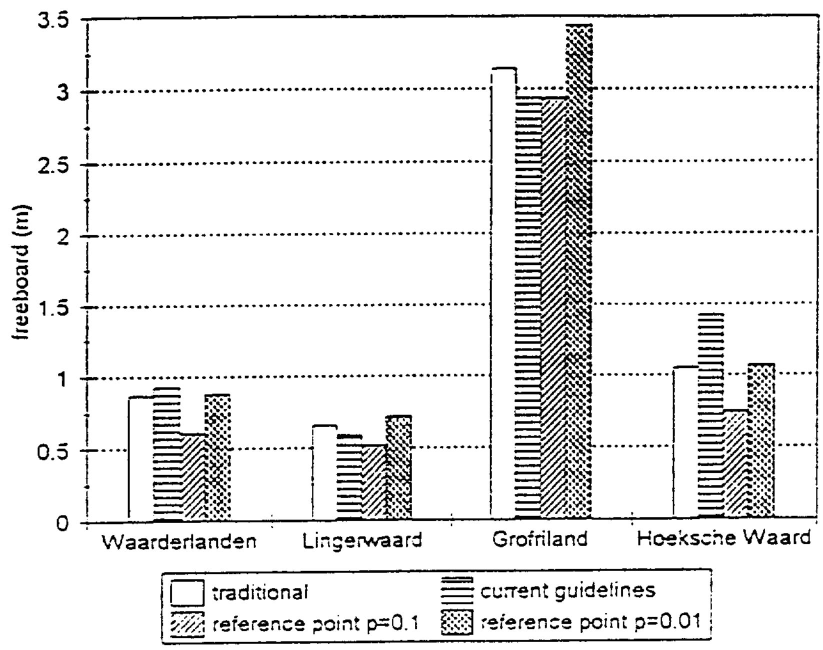


*Figure 4 Mean freeboard for 4 different methods*

For Kabeljauwsche Waard the reliability indices of sliding for 5 dike sections are given in figure 5. The reliability index for the reference point is calculated with $\xi_i=\xi/4=0.01/4$ (division by 4 because there are 4 relevant failure mechanisms besides overtopping), N=1 and the legal standard 1/2000 (see formula 3).

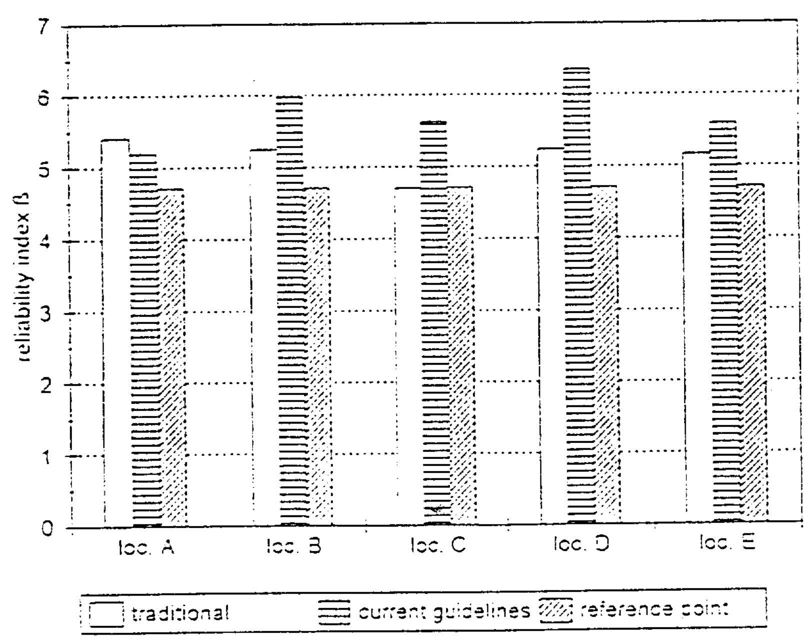


*Figure 5 Reliability index for sliding for 3 different methods*

Figure 5 shows that in general the traditional method and the provisional reference point are more or less consistent, while the current guidelines are a bit safer.

## 7. CONCLUSIONS

A first comparison of design methods was made to investigate the possibilities to set a clear reference point to calibrate a new safety philosophy. For overtopping the before hand indicated value for the degree of freedom of the reference point (p=0.01-0.1) give results which do not deviate much from former design methods. For sliding the provisional reference point is less demanding then the current method. A more thorough analysis must be made before the reference point can be set.

A level II system analysis to calculate the flooding probability of a polder is possible, but the improvement of the models to describe failure mechanisms is necessary.

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