Delft Cluster

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Author:	Ir W. Roos	Institute:	TNO Bouw

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Abstract

The damage to buildings caused by floods has been studied more often. Several studies researched the relation between damage and water depth, the so called "damage factor". Whereas the amount of damage will not only be caused by the water depth but also by, for instance, the water velocity. Therefore in other studies a start has been made to include flood factors like the water velocity in calculation models. Some of these models are based on the comparison of the loads on the structures with the strength of the structures. In this study this comparison has been utilized further for masonry and concrete buildings in the Netherlands. Besides the comparison of load and strength, which may cause the failure of a wall, also the scour of a foundation has been looked at. These two failure mechanisms, failure of walls and scour of the foundation, are thought to be the most relevant mechanisms for the Netherlands. Therefore a model has been made which calculates the possibility of partial collapse by these two failure mechanisms. The loads which has been researched, in relation to the failure of walls, are loads by hydrostatic and hydrodynamic pressure, wave action and pounding debris. For some of these loads the magnitude of these loads are subject to the location. Also the type and number of buildings are subject to the location. Therefore the model has been related to a geographical information system. This way for each location (in this case a postal code area) the amount of damage can be specified.

The model has been applied to the case "Midden Holland". This case represents a dyke breach at Krimpen. From the model it appears that due to this dyke breach damage to buildings will occur. The damage ranges from 80 percent partial damaged buildings in some postal code area's near the breach to no damage in postal code area's further away (approximate distance 16 kilometer) from the breach.

Damage curves (velocity – depth) has been derived from the model. From these curves it appears that from the failure mechanisms investigated in this study, the failure mechanism "failure of walls" will cause the most damage. Damage by scour of the foundation is only a fraction of the damage caused by the failure of walls. The loads applied to the walls by debris appears to be the most damaging. Wave action does not cause damage at all and the loads due to water velocity and water depth have less impact on the structures than debris. Therefore the damage curve for the failure mechanism "failure of walls" is totally dictated by the damage curve given by the load of pounding debris.

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Executive Summary

Floods may have a damaging effect on buildings. This will cause economical loss and, if the building collapses, may also cause fatalities. Therefore it is important to quantify the damage to buildings. From other studies is appears that the amount of damage to buildings caused by a flood depends on many factors. The most important factors are the flood factors (e.g. water depth, water velocity) and the building factors (e.g. number of buildings, type of structure). The magnitude of the flood factors are related to the location. For instance the water velocity in the first hour after a dyke breach will be much higher than the water velocity further away from the breach. The building factors are related to the location as well. Therefore, in this study, a model has been derived which quantifies the damage to buildings and is related to geographical information system. This model has been applied to one case “Midden Holland”, which represents a dyke breach at Krimpen.

The model quantifies the damage to buildings caused by the failure mechanisms, failure of walls and scour of the foundation. These failure mechanisms are thought to be the most relevant for the Dutch situation. Failure of walls may occur is the The initiation of a failure mechanism depends on the interaction between (some) flood factors and the building factors.

It is supposed that the failure mechanisms, scour of the foundation, will occur if the top layer of the soil washes away and the affected building is built on a shallow foundation. Therefore several types of top layers has been described for which critical water velocities are determined. These water velocities initiate the layer to wash away. If this water velocity is during the flood scour of the buildings built on shallow foundation will occur.

The failure of walls depends on the loads applied to the buildings and the strength of the buildings. In this study four load cases are researched:

1. Hydrostatic pressure due to water level difference inside and outside the building
2. Velocity of the incoming water
3. Wave action
4. Pounding debris

The applied loads to the buildings are (in this case) all related to the flood factors and the strength of the buildings depend on the building factors. If the load on the buildings exceed the strength of the building the building will collapse (partial).

To quantify all the factors, which affect the two failure mechanisms, two databases and the hydraulic model Delft FLS have been used (respectively for quantifying the building factors and flood factors). For each postal code area within the area of the case “Midden Holland”, the model generates the building factors from the two databases and combines this data with the flood factors for these postal codes. On the basis of these factors the occurrence of the failure mechanisms can be determined.

The (partial) collapse due to scour of the foundation has been calculated by the model as follows. The water velocity, which occurs in a certain postal code, has been compared with the critical water velocity of the top layer of the soil, which is found in that certain postal code. If the water velocity exceeds the critical water velocity the buildings built on shallow foundations will (partly) collapse.

The (partial) collapse due to failure of walls has been calculated by the model as follows. It is supposed that the loads are applied in right angles to a load-bearing wall of the buildings. Furthermore it is supposed that the first floor height is equal to the surface level. The bending moments and shear forces, which are applied to the buildings by the distinguished load cases, have been compared with the strength of the buildings in terms of bending moments and shear forces.

The output of the model consists of the percentage of partial collapsed buildings (e.g. collapse of one load-bearing wall or scour of foundation) due to the failure mechanisms, failure of walls and scour of the foundation. It is supposed that 70% of the partial collapsed buildings will collapse totally.

It appears that scour of the foundation will occur in 31% of the postal codes areas of the case “Midden Holland”. In these postal code areas less then 5% of the buildings will be partial damaged due to scour of the foundation. The damage mechanism failure of walls appears to have more impact on the buildings in the flooded are. In 16% of the flooded postal codes more then 5% of the buildings will partial collapse by this mechanism. At approximately 16 kilometers from the breach no damage will occur.

Finally, damage curves have been derived from the model for the failure mechanism “failure of walls”. From these damage curves can be concluded that the load case, pounding debris, dictates the model. Therefore it is recommended to minimize the uncertainties in the flood and building factors in total and especially these factors on which the load case “pounding debris” has been based.

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BASISPROJECT NAAM:	**Flood consequences and acceptability**	BASISPROJECT CODE:	**02.03**
THEMA NAAM:	**Risk of flooding**	THEMA CODE:	**02**

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α	Material factor	-
α_{floor}	Geometrical factor floor	-
α_{roof}	Geometrical factor roof	-
γ_d	Load factor roofs	-
γ_w	Load factor residential parts	-
ϕ_κ	Mean diameter of steel bars	mm
ρ	Density	kg/m^3
ρ_f	Density of floor	kg/m^3
$\rho_{\underline{w}}$	Density of wall	kg/m^3
$\sigma_{\underline{c}}$	Compressive stress	N/mm^2
τ	Shear stress	N/mm^2
ω_o	Reinforcement percentage	-
A	Area	m^2
c	cover on reinforcement	mm
C_D	Drag coefficient	-
d	Depth of water	m
d_r	Depth of room	m
d_w	Depth of building	m
E	Young's Modulus	Pa
$f'_{b,gem}$	Mean compressive strength concrete	N/mm^2
$f'_{b,gem,upgr}$	Mean upgraded compressive strength concrete	N/mm^2
f_t	Tensile strength	N/mm^2
f_v	Shear strength	N/mm^2
F_d	Force by crashing debris	N
F_s	Hydrodynamic force	N
F_g	Wave force	N
F_H	Horizontal load	N
F_w	Hydrostatic force	N
$\sum F$	Sum of forces	N
g	Acceleration of gravity	m/s^2
h_{fo}	Foundation height	m
H_s	Significant height of wave	m
I	Moment of area	m^4
k	Spring rigidity	N/m
l	Height of floors (floor to floor)	m
m	Mass	kg
M	Bending moment	Nm
n	Number of floors	-
N_d	Normal force	N
N_s	Force in concrete steel	N
P_f	Probability of collapse of a building by waves	-
P_s	Probability of storm	-
p_g	Wave pressure	N/m^2
p_s	Hydrodynamic pressure	N/m^2
p_w	Hydrodynamic pressure	N/m^2
R	Reaction	N
q_d	Live loads roofs	N/m^2
q_{sl}	Surface load	N/m^2
$q_{sw,fl}$	Self weight floor	N/m^2
$q_{sw,rf}$	Self weight roof	N/m^2
$q_{sw,wl}$	Self weight wall	N/m^2
q_w	Live load residential parts	N/m^2
r	Protection factor	-

t_f	Thickness of floor	m
t_u	Useful thickness of wall	mm
t_w	Thickness of wall	m
v	Water velocity	m/s
V_u	Applied shear forces	N
W	Approximate weight of the structure	kg
w	Width	m
x_u	Compressive zone height	mm
x_{zwp}	Point of application	m
$x_{zwp,1}$	Point of application hydrodynamic force	m
$x_{zwp,2}$	Point of application hydrostatic force	m

1 Introduction

Buildings along the Dutch coast and rivers are at risk from flooding. In general a flood will cause direct material damage to buildings. Furthermore a building could even collapse by, for instance, wave action. The aim of this study is to quantify the damage to buildings caused by a flood. It has been applied to one case: "Midden Holland" (see Figure 1). This case represents a dyke breach at Krimpen.

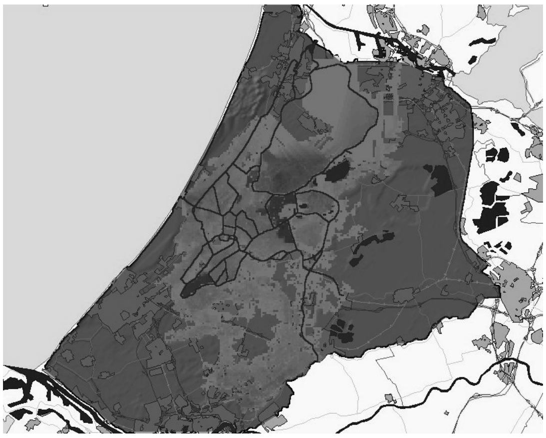

Figure 1 Case "Midden Holland"

It is important to quantify the damage to buildings for determining the economical loss, But also for people living in these buildings who may be killed by the collapse of a building. To quantify the damage, the failure mechanisms initiated by floods must be mapped and modeled. Which failure mechanism occurs depends on many factors but basically on flood factors (e.g. water velocity, water depth) and building factors (e.g. number of buildings, building type, type of structure). Because both type of factors are subject to the location, a geographical information system (GIS) could be the basis to model the mechanisms. Hydraulic models, which are already related to GIS, can provide the flood factors. By relating the building factors to GIS as well, a model can be derived which determines the possibility of partial and total collapse of buildings by several failure mechanisms.

In this study a model will be made for quantifying the damage to buildings caused by floods. In this report the derivation of this model will be described. In chapter two existing damage models, which quantify the damage to buildings by floods, will be described. In chapter three the derivation of the model will be described and in chapter four the conclusions will be given.

2 Damage models

So far the quantification of the damage to buildings caused by floods has mostly been calculated by damage functions (e.g. Vrisou van Eck et al., 1999). The damage functions attach a "damage factor", which indicates the amount of damage to the buildings in monetary terms, to a certain water depth. Most of these damage functions are based on one of the two methods that are described by Molenaar et al., 2002.

- Method Duiser
- Method Penning-Rowsell

Briefly, the difference between these methods is the kind of data that is used for calculating the damage factor. The first method uses data from former floods while the second one uses computational data that has been calibrated by a case study.

The damage functions result in a damage factor, which is only related to the water depth to which the buildings are subjected. In practice not only water depth but also water velocity and wave action may cause damage. These extra factors have so far only been considered in a limited extent (e.g. Maijala et al., 2001). In Vrouwenvelder et al., 1994, a start has been made to calculate the hydraulic loads on the structure and the strength of the structure for several types of structures (difference in used materials). These calculations are very primitive, because of a frequently lack of data about loads and strength. However a formula is given for calculating the possibility of the collapse of a building by waves.

$$P_f = P_s \alpha 10^{-3} d^{1,8} r \qquad (1)$$

Where:

P_f = probability of collapse (-)
P_s = probability of storm (for example more then wind force 8) (-)
α = material factor (-)
d = depth of the water (m)
r = protection factor ($m^{-1,8}$)

In the final report of the RESCDAM project, by Mijala, et al., 2001 several studies are mentioned in which damage criteria were set up which also do take the velocity into account. These studies are summarized below.

For several frame houses (difference in storeys and weight) a damage criteria was found in “Flood proofing rural residences” by Black, 1975. Data was used of the Chemung river flood in the USA during the tropical storm Agnes in 1972. The researched frame houses were classified in nine categories to define an approximate weight, *W*, for each structure. The damage to the structures was classified either “survived” or “destroyed”.
For each structure the horizontal load applied to the structure, F_H (N), was calculated and divided by the weight of the structure.

$$F_H = C_D 0{,}5 \rho v^2 \left(d - h_{fo}\right) \qquad (2)$$

Where:

C_D = drag coefficient = 2
ρ = water density (kg/m^3)
v = velocity (m/s)
d = depth of water (m)
h_{fo} = foundation height (m)

Also the corresponding normal force parameter ($d-h_{fo}$)/ (10s), where s represents the number of structural storeys, on each of the structures was calculated. These two parameters (applied load and normal force) presented in a figure results in a clear and general separation between the destroyed and survived structures.

Black, 1975, calculated the maximum bending moments for timber frame houses produced by the hydrostatic and dynamic pressure. A water depth of 0.9 m will already attain the maximum bending moment for the frame even when the velocity is not taken into account. If the water enters the house the hydrostatic pressure will equalize on both sides of the wall and is effectively cancelled. Then the maximum bending moments will be attained by a water depth of 2.2 m and a velocity of 1,5 m/s or 1 m and a velocity 2,4 m/s.

In “The development of criteria for predicting dam break flood damages using modeling of historical dam failures” by Clausen et al., 1990, a criterion was developed for predicting dam break flood damages for brick and masonry buildings. This criterion has been based on the data from the Dale Dyke dam failure in the UK in 1864. Water velocities, *v (m/s)*, and depths, *d (m)*, for this flood were calculated and the damage, which occurred by this flood, was determined from the details published by Harrison (1864). The damage was divided in inundation damage, partial damage and total destruction. The criterion gives a damage parameter, *vd* (m^2/s), which indicates the boundaries between different damage categories.

Based on the studies described above a recommendation for Finnish houses was given in the RESCDAM project. The damage criteria for wood-framed, and masonry, concrete and brick houses consist of the velocity times depth parameter, *vd*, which has been introduced by Clausen et al., 1990.

In some of the studies described above (Vrouwenvelder et al., 1994, Black, 1975) the damage to buildings has been calculated by comparison of the strength of the buildings with the loads on these buildings. The strength depends on building factors, like type of structure and type of building. The loads, which were mentioned in the studies, were from several sources, like wave action, water velocity and water depth. This approach (comparison of strength and loads) will also be used in the model created in this study. Besides that the damage parameter, *vd*, given in Clausen et al., 1990, and also used in the RESCDAM project, will be examined on its usability in the Dutch situation (e.g. a dyke breach instead of a dam failure).

3 The model

As stated in the previous chapter it appears that several flood factors (i.e. water velocity, water depth) and the combination of factors may result in damage to buildings. Therefore, to investigate the relation of these flood factors with the damage to buildings, a model has been created which calculates the damage of buildings caused several flood factors. There are many failure mechanisms, which may be initiated by these flood factors. From historical data and other studies it is concluded that the failure of walls, is one of the mechanisms, which may be initiated by a flood. The comparison of loads on buildings with the strength of buildings, which was performed by several studies described in the previous chapter, describes this mechanism. Another mechanism, which may occur, is the scour of the foundation by water velocity. These two mechanisms (see Photo 1) are thought to be the most relevant mechanisms for buildings in the Netherlands. Therefore the model describes them. An overview of the model is given in Figure 2.

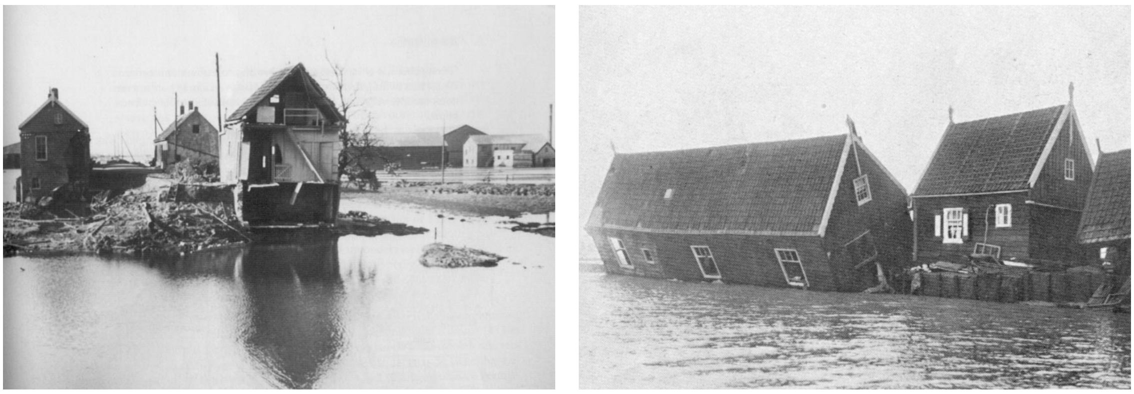

Photo 1 Example of the two failure mechanisms during the floods in the Netherlands (left hand: failure of walls in February 1953(Allewijn, 1983), right hand: scour of foundation in January 1916 (Boon, 1916))

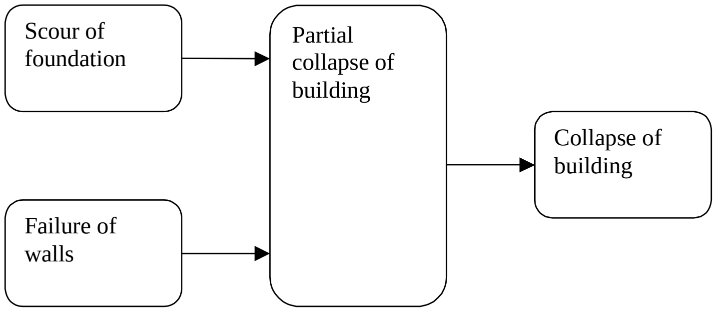

Figure 2 Flow chart of total model

As stated before the occurrence of the mechanisms described above will depend on a great many factors. Therefore, to visualize the interactions between the different factors flow charts have been made for both mechanisms (Figure 4 and Figure 5), which will be discussed separately in the following paragraphs.

3.1 Scour of the foundation

Scour of the soil may easily occur if the top layer of the soil washes away by the velocity of the water. This will not affect piled foundations. Yet foundations with a shallow construction depth are sensitive for this mechanism. These buildings may turn over to one side (see *Photo 2*) or damage a part of the foundation and wall. Figure 3 illustrates the failure mechanism and in Figure 4 the flow chart is given.

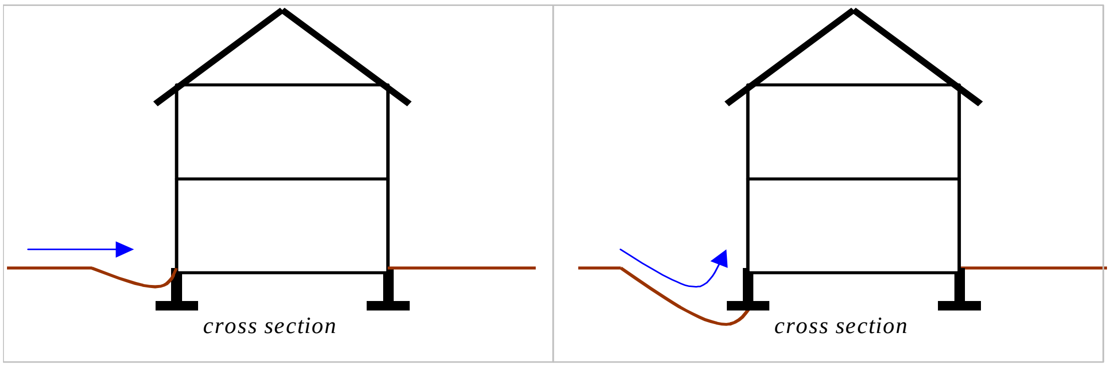

Figure 3 Illustration of failure mechanism "Scour of foundation"

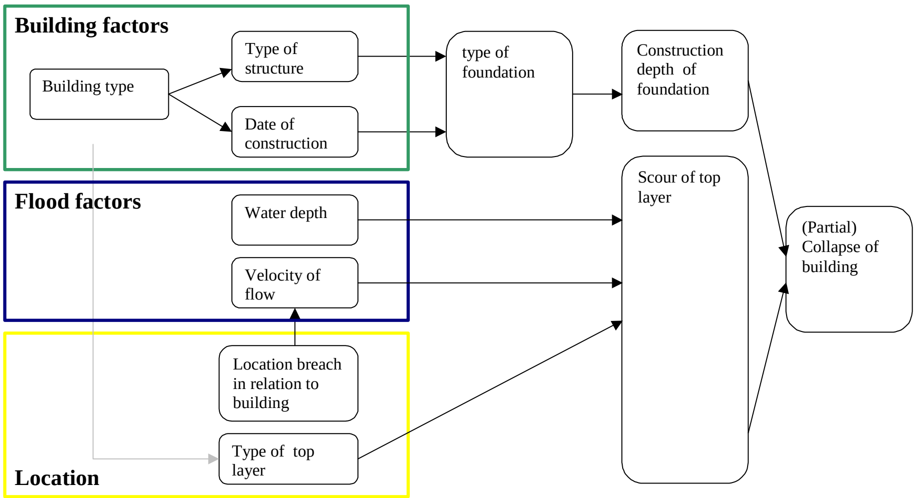

Figure 4 Flow chart: Scour of the foundation

To model this failure mechanism data about building factors, flood factors and factors subject to the location mentioned in the flow chart above will be needed. The data used in this model will be described in paragraph 3.3.

Photo 2 Scour of the foundation during the flood in August 2002 in Germany(Reimer, 2002)

3.2 Failure of walls

The approach given in chapter 2 will be in this study to calculate the failure mechanism, “failure of walls”. This approach implies the comparison of the load on the buildings with the strength of the buildings, as shown in *Figure 5*.

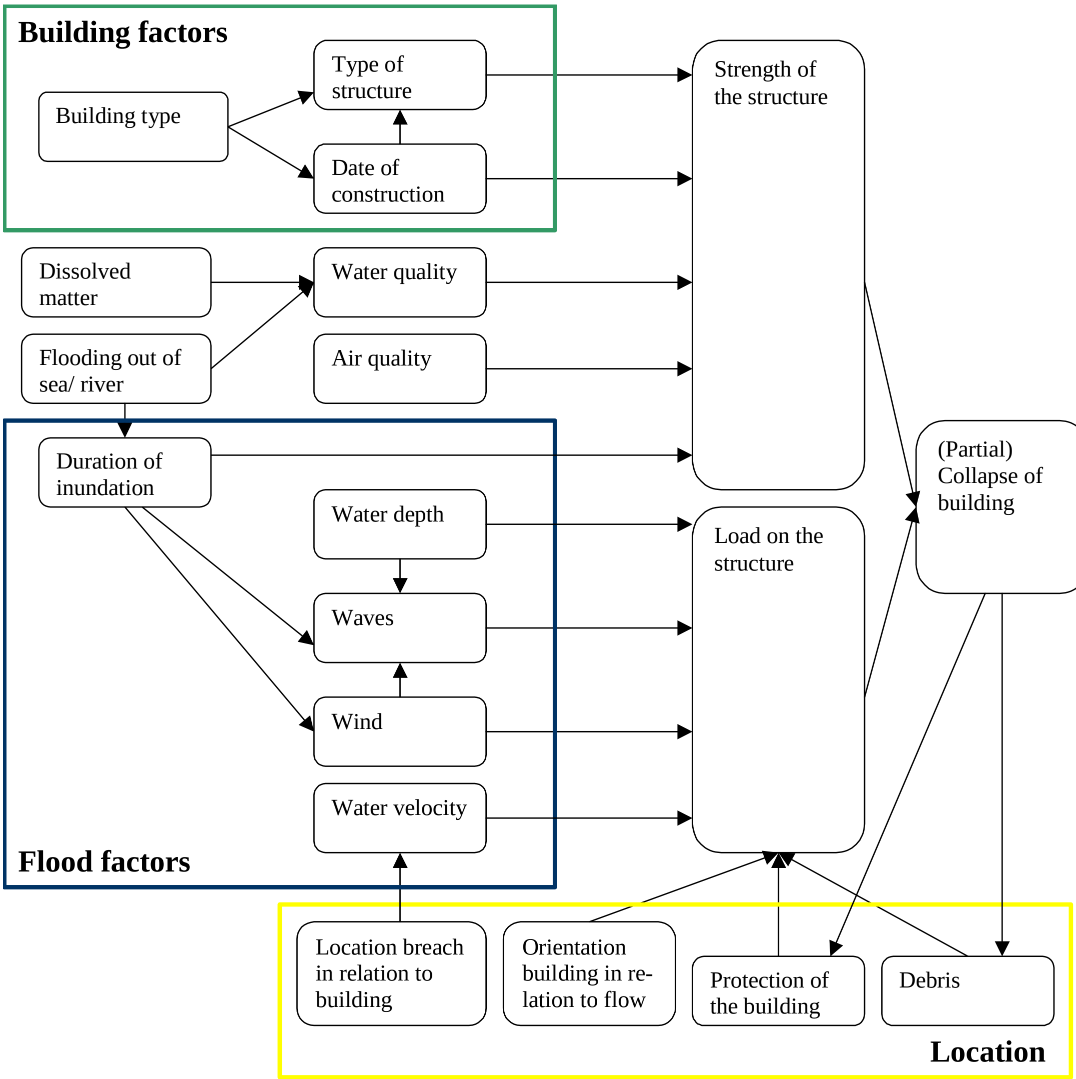

Figure 5 Flow chart: Failure of walls

In this study four load cases are researched:

1. Hydrostatic pressure due to water level difference inside and outside the building
2. Velocity of the incoming water
3. Waves action
4. Pounding debris

It is supposed that these loads are applied in right angles to a load-bearing wall of the buildings (see Figure 6). Furthermore it is supposed that the first floor height is equal to the surface level.

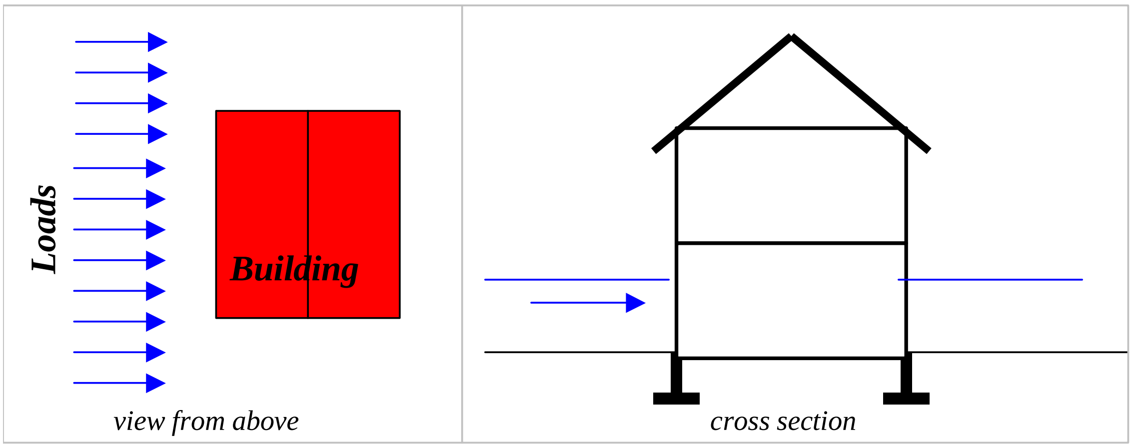

Figure 6 Position of building in relation to the loads

The first mentioned assumption might cause some uncertainties because of most buildings only two of the four exterior walls will be load-bearing (see Figure 7). It is therefore also possible that the loads described above will hit the non-load bearing exterior wall. Due to the lower strength this wall may be demolished more easily than load bearing walls. Besides that the collapse of a non-load bearing exterior wall will probably have less impact on the whole building, i.e. if a load bearing wall collapses it is more probable that the whole building will collapse. Therefore in this model it is supposed that if a load bearing wall collapses (partial collapse) in 70% of the cases the whole building will collapse.

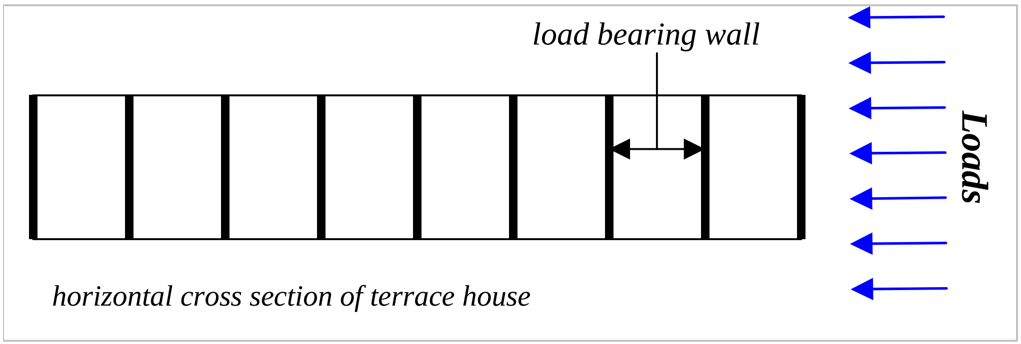

Figure 7 Loads on terrace house

Photo 3 Failure of walls during the flood in August 2002 in Germany (Reimer, 2002)

3.3 Input data

The input data given in the flow charts (Figure 4 and Figure 5) has been clustered in building factors, flood factors and factors that are subject to the location of the flood. Before explaining the operation of the model this input data will be described more in detail.

3.3.1 Building factors

The behavior of a building during a flood depends mainly on the kind of structure. A database (MEB), which provides direct information about the structures used in the Netherlands, has been used in this study to describe the structures. This database has been developed by TNO on the authority of VROM (Dutch Ministry for Housing, Regional Development and the Environment) and provides data about the building stock in the Netherlands. The building stock is divided by building type, type of structure and date of construction (Table 1) but is not related to a geographical information system (GIS). Because the MEB database is not linked to geographical units, the provided data obtains for the Netherlands in general.
To relate the MEB database to GIS, the database has been combined with another database (Bridgis), which relates building types to geographical units. These units consist of addresses with equal postal codes (six (street), five (neighborhood) or four numbers (district)). Per unit the predominant building type and the number of buildings is given. The building types, which are used in this database, are given in Table 2.

Building type
Single family dwelling, 1 floor
Single family dwelling, 2 floors
Single family dwelling, > 2 floors
Block of flats with an entrance hall
Gallery flats
Maisonnettes
Other more family dwellings

Type of structure	
Traditional way of building (solid walls)	TB
Traditional way of building II (cavity walls)	TB2
Timber frame	TF
Cast concrete	CC
Prefabrication	PF

Date of construction
Before 1905
1905-1919
1920-1929
1930-1944
1945-1949
1950-1954
1955-1959
1960-1964
1965-1969
1970-1974
1975-1979
1980-1984
1985-1989
1990-1994
1995 ……..

Table 1 Data in MEB database

Building type
Unknown
Detached houses/ bungalows
Two semi-detached houses
Terrace houses
Block of flats, 4 or less floors
Block of flats, more than 4 floors
Apartments/ maisonnettes
Apartments/ apartments in canal side house
Residences/ canal side houses
Independent old peoples flats
Farmhouses
Student houses / block of flats
Houseboats
Caravans
Various

Table 2 Building types given by the Bridgis database

The stock numbers from the MEB database have been converted into percentages. This way the output of the Bridgis database (amount of buildings of a certain building type per geographical unit) can be used as the input of the MEB data. Therefore the Bridgis building types must be converted into the MEB building types. The used conversion has been based on expert opinion (see Table 3). For example 90% of the terrace houses given by Bridgis will be converted into single family dwellings with 2 floors.

MEB / **Bridgis**	Single family dwellings 1 floor	Single family dwellings 2 floors	ingle family wellings more han 2 floors	Block of flats with an entrance hall	Gallery flats	Maisonnettes	Other more family dwellings
Unknown	14%	14%	14%	14%	14%	14%	14%
Detached houses/ bungalows	50%	30%	20%				
Two semi-detached houses	10%	90%					
Terrace houses		90%	10%				
Block of flats, 4 or less floors				50%	50%		
Block of flats, > 4 floors				25%	75%		
Apartments/ maisonnettes						100%	
Apartments			50%	50%			
Residence / canal side house			50%				50%
Independent old peoples flats	10%	10%			80%		
Farmhouses	100%						
Student houses / block of flats					100%		
Houseboats							
Caravans							
Various	14%	14%	14%	14%	14%	14%	14%

Table 3 Conversion of the Bridgis building types into the MEB building types

The houseboats and caravans are not divided over the MEB building types because it is assumed that these building types will respectively drift away or be demolished directly.
The combination of the two databases results in an overview per postal code like shown in Table 4.

		Date of construction				
Building type	**Type of structure**	Before 1905	1905-1944	1945-1974	1975-1994	1995-2002
Single family dwelling, 1 floor	TB	2	5	1	0	0
	TB2	0	0	8	11	4
	CC	0	0	4	5	1
	TF	0	0	1	1	0
	PF	0	0	0	1	0
Single family dwelling, 2 floors	TB	15	36	7	0	0
	TB2	0	2	49	37	14
	CC	0	1	21	19	5
	TF	0	0	6	3	1
	PF	0	0	0	2	1
Single family dwelling, more than two floors	TB	5	13	2	0	0
	TB2	0	1	23	34	13
	CC	0	0	11	17	4
	TF	0	0	3	3	1
	PF	0	0	0	2	1
Block of flats with an entrance hall	TB	140	134	42	0	0
	TB2	0	141	742	168	71
	CC	0	3	186	138	44
	TF	0	1	78	39	15
	PF	0	0	0	0	0
Gallery flats	TB	7	8	86	0	0
	TB2	0	4	1200	1098	452
	CC	0	1	256	448	135
	TF	0	0	53	51	16
	PF	0	0	0	0	0
maisonnettes	TB	114	110	9	0	0
	TB2	0	116	165	42	14
	CC	0	0	30	83	37
	TF	0	0	29	59	18
	PF	0	0	0	0	0
Other more family dwellings	TB	4	4	0	0	0
	TB2	0	5	9	9	4
	CC	0	0	1	3	1
	TF	0	0	0	0	0
	PF	0	0	0	0	0

Table 4 Example of the number of buildings per postal code divided into building type, type of structure and date of construction

As can be seen in Table 4 the combination of the two databases gives the full set of building factors, which are mentioned in the flow charts and are necessary for deriving a model.
The buildings will be distinguished per postal code area by building type (7), type of structure (5) and date of construction (5). The focus in this study is on structures of masonry and concrete because these structures are in large numbers present in the building stock of the Netherlands. Therefore timber frame houses (TF in the table) are left aside. Besides that the ranges given in the MEB database for the date of construction are chosen larger for the model. Smaller ranges will not refine the information (e.g. material properties) related to this data.

3.3.2 Flood factors

The flood factors which will initiate the failure mechanisms are schematized in the flow charts (Figure 4 and Figure 5) and consists, for these two failure mechanisms, of the following flood factors:

1. Water velocity
2. Water depth
3. Wave height (which is related to wind and water depth)

The magnitudes of the first two flood factors caused by a dyke breach near Krimpen (Figure 1) are calculated using the hydraulic model Delft FLS. The results of the calculations with Delft FLS are shown in Figure 8 and Figure 9 in which respectively the maximum water depth and maximum water velocity are shown.

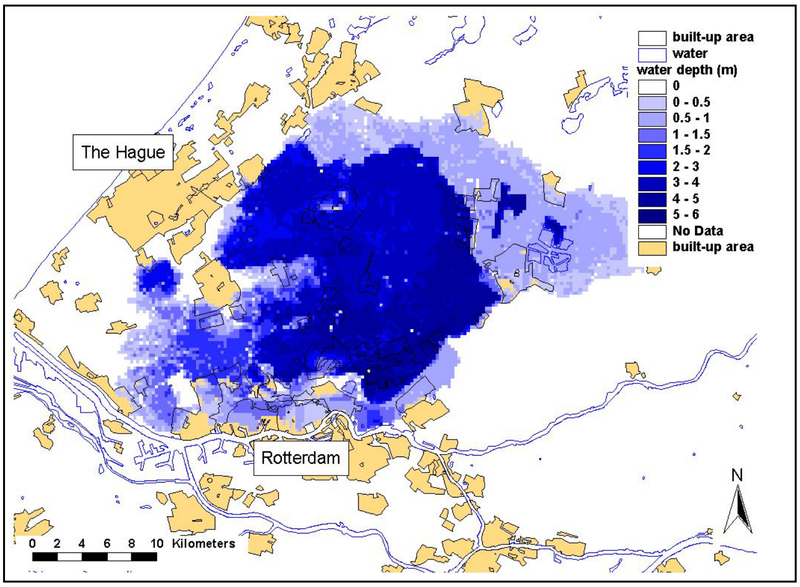

Figure 8 Maximum water depths

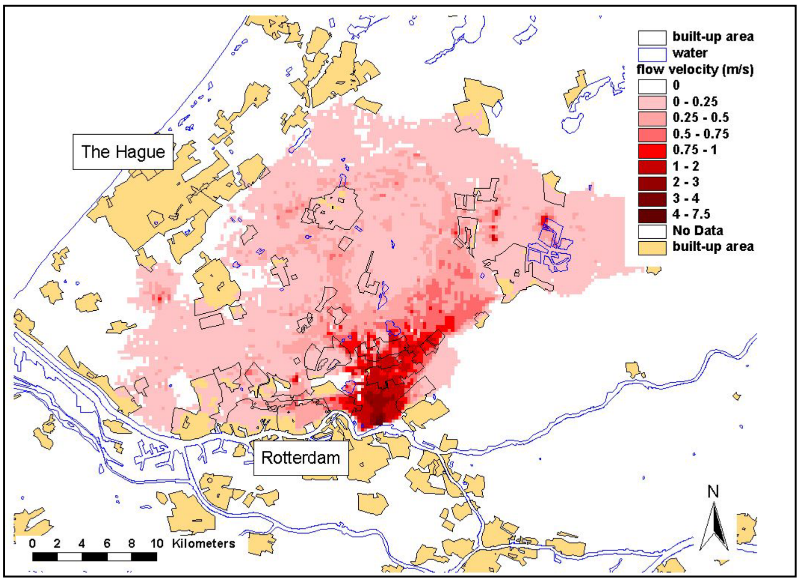

Figure 9 Maximum water velocities

By combining these maps with a postal code map, the maximum water depths and maximum water velocities per postal code can be defined. Similarly the water depths and velocities on specific time intervals can be defined. The height of the waves which may occur during the time the area is flooded has been calculated from the water depth (by Delft FLS), the wind-force and fetch length. The possible wind-force during a certain time can be estimated by statistical information and the fetch length has been related to the building density. These calculations will be explained in paragraph 3.4.2.4.

3.3.3 Other factors

Besides the discussed building and flood factors other factors like factors related to the specific situation of the building may be of influence on the amount of damage as well. In the flow charts in Figure 4 and Figure 5 some of these factors are already indicated (location). The relation of these factors to the damage to buildings will now be described [1].

Location breach in relation to building

The high velocity of the water flow in the direct vicinity of the breach may have a demolishing impact on all the objects in this area. This factor is therefore directly related to the velocity of the water.

Orientation building in relation to the flow

If a building is at right angles to the water flow the loads on the structure will be the biggest by comparison with other angles. In this study it is assumed that the load bearing walls are at right angles to the water flow. With regard to the scour around the foundation, the orientation of the building will also have an influence on this mechanism.

Protection of the building

The load on the structures will change when other objects disturb the water flow. Therefore the protection of the buildings will affect the load on the structure.

Debris

Debris will be carried along the water and may cause damage to affected buildings by crashing into the buildings. The forces will depend on the weight of the debris and the velocity of the water flow. The damage caused by the debris can range from material damage to collapse of the building. Also “debris” inside houses must be taken into account. For example heavy furniture that start to float and crash into the walls because of wave action.

Water quality

A difference can be made in water quality between freshwater and saltwater and also contaminated water. Because of the fact that the structures are exposed to water, it is important to know its impact on the material properties. The effects of exposing brick and concrete to freshwater, saltwater or contaminated water is summarized below.

<u>Brick</u>

The flood disaster, which hit the southwestern part of the Netherlands in 1953, gives information about the effect of saltwater to masonry buildings. Some time after the disaster the brickwork started chipping off. This phenomenon can be explained by salt crystallization of mainly NaCl and Na_2SO_4.

Another more direct (within a year) damage is frost damage. If the brick is still wet (fresh, salt or contaminated), frost can damage the material because of the expansion of the water by freezing (see *Photo 4*).

[1] These factors have not been taken into account in the model because of the difficulty to relate these factors to a geographical information system.

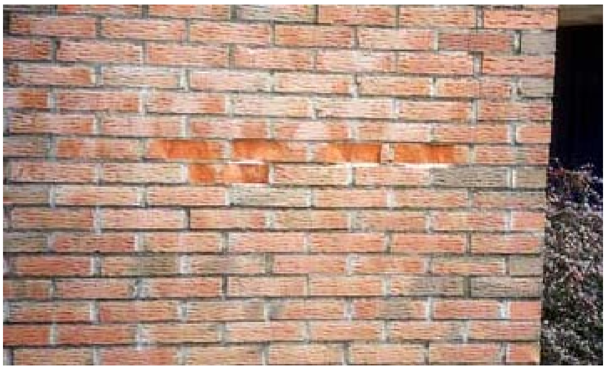

Photo 4 Frost damage

Concrete

Reinforced concrete that has been subjected to saltwater can be affected by chloride-induced corrosion. Chloride induced corrosion causes cracks and brown colouring of the concrete. When and if the damage occurs depends on the rate of diffusion of the chloride into the pores of the concrete. The damage will not affect directly the structural properties of the material but because of the possible progress of the corrosion it is necessary to protect or repair the surface to prevent the building from further damage. By Polder et al., different methods are described to repair the affected concrete.

Air quality

No relations have been found between air quality and the two investigated mechanisms. It is not known if any of the structural materials will decay by certain contaminations in the air.

3.4 Operation of the model

On the basis of the described building and flood factors the model will determine the number of buildings, in every postal code area, which will partly collapse due to the two failure mechanisms. Therefore the model generates for each postal code in the flooded area the building factors from the two databases and combines this data with the flood factors for these postal codes. The flood factors consist of the water velocity and water depth for the first six hours after the dyke breach, wind speed and fetch length. The processing of these factors in the model will be described on the basis of the two failure mechanisms, scour of the foundation and failure of walls.

3.4.1 Scour of foundation

To determine the number of buildings in the flooded area, which may be affected by this mechanism, the percentage built on shallow foundations for each building category given in Table 4 have been estimated (Table 5). These percentages are estimated for this case (Midden Holland) only. The scour depends on the type of top layer that is found around the buildings. Six kinds of top layers have been distinguished for which critical water velocities are given in Table 6. These water velocities initiate the layer to wash away.
It is supposed that a relation can be found between the type of top layer around buildings and the number of buildings in that area. The top layer around farms (1 building per ha), for instance, will differ from the top layer around flats (>51 buildings per ha). Therefore, the type of top layers, which are present around the buildings in a certain postal code area, has been estimated by relating this to the building density for that area (Table 7). It is supposed that when the top layer washes away scour of the foundation will occur.

type of structure	Before 1905	1905-1944	1945-1974	1975-1994	1995-2002
TB	30%	20%	0%	0%	0%
TB2	20%	10%	0%	0%	0%
CC	0%	0%	0%	0%	0%
PF	0%	0%	0%	0%	0%

Table 5 Percentage of buildings which is built on shallow foundations for each building type

	Mould / Sand	Clay / Gravel	Grass / Paving
v (m/s)	> 0.20	> 0.60	> 5.00

Table 6 Critical water velocities

Building density (/ha)	Top layer		
	Mould / Sand	Clay / Gravel	Grass / Paving
0-1	60%	10%	30%
2-10	50%	5%	45%
11-25	40%	5%	55%
26-50	30%	5%	65%
>51	20%	5%	75%

Table 7 Estimation of type of top layers around the buildings

3.4.2 Failure of walls

To determine the number of buildings that will be affected by this failure mechanism the loads on the buildings and strength of the buildings will be compared. This comparison will be carried out by comparison of the applied bending moments and shear forces with the capacity of the structures in terms of bending moments and shear forces based on average material properties.

The applied bending moments and shear forces to the walls, by the four load cases (described in paragraph 3.2), depend on the type of structure. Therefore, three mechanical models have been set up to describe the structures (Figure 10). A fourth model (model D) has been added to describe load case two “Hydrostatic pressure due to water level difference inside and outside the building” this will be explained later in paragraph 3.4.2.2.

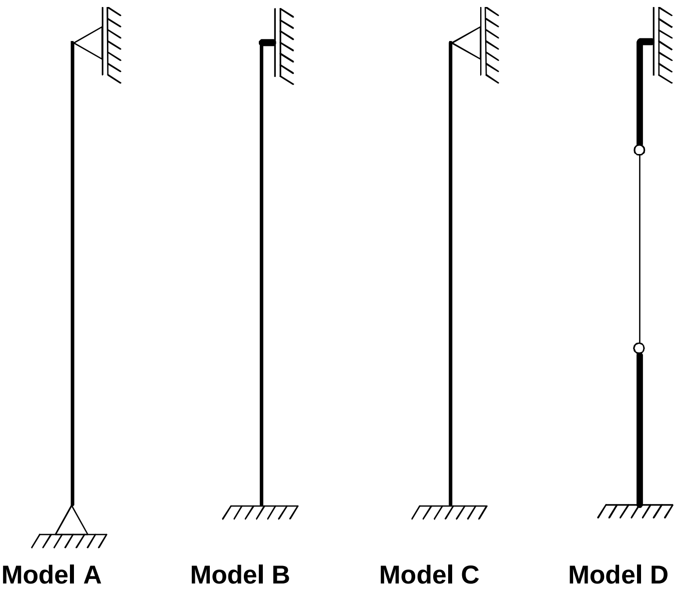

Figure 10 Mechanics schemes

The models are applied to the distinguished types of structure, given in paragraph 3.3.1, as listed below.

Traditional way of building I → Model B
Traditional way of building II → Model B
Cast concrete → Model B
Prefabrication → Model A

There are two exceptions on this assignment:

- For single-family dwellings with one floor built in the traditional way of building I or II, model C is applicable.
- For the second floor of single-family dwellings with two floors built in the traditional way of building I or II, model C is also applicable.

These exceptions are introduced because it is assumed that these building types will have a saddle roof which joint is schematized as a hinge. In the following paragraphs the calculation of the applied loads on the structures will be described for each load case.

3.4.2.1 Load on the structures

The bending moments and shear forces induced by the four load cases have been calculated for each of the models from basic structural mechanics equations. The input for these calculations is the water velocity and corresponding water depth for each postal code for the first six hours (Figure 11). In the following paragraphs the calculations for each load case has been given.

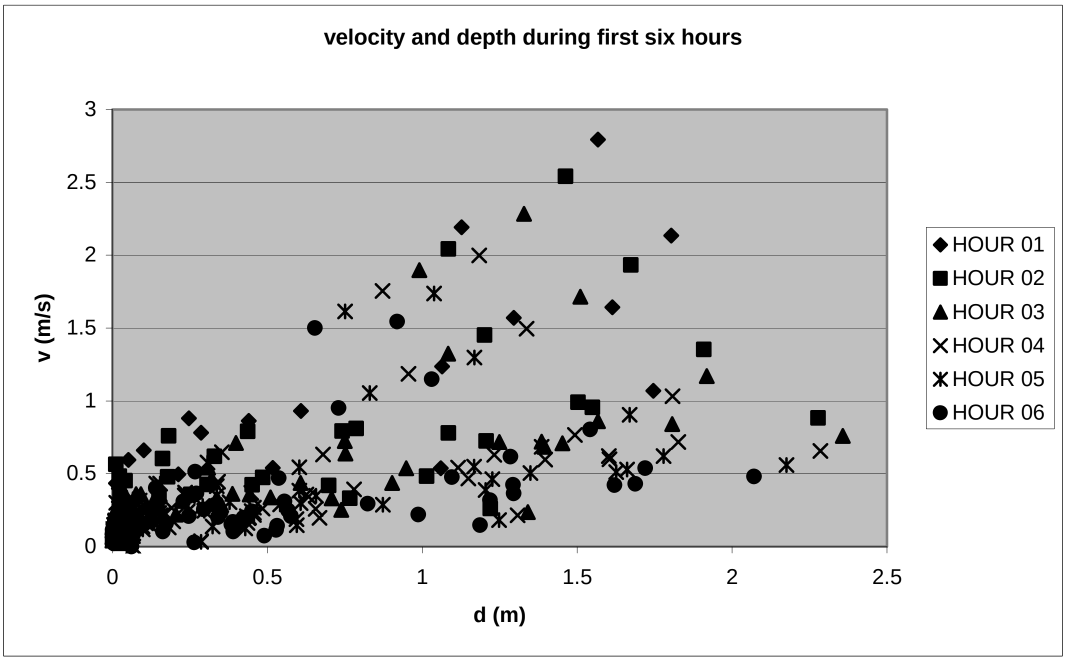

Figure 11 Water velocity and corresponding water depth on the first six hours

3.4.2.2 Hydrostatic & hydrodynamic pressure

During the fill up of the flood plain the buildings will be subjected to a hydrostatic pressure until water enters the house and no difference in water level inside and outside the building is present. At that moment the hydrostatic pressure will equalize on both sides of the wall and is effectively cancelled. It is supposed that for some time a difference in water level will always occur. Therefore, the moment of equalization is estimated to be at the moment that the lower level of the window openings has been reached.

To describe this situation model D has been added to the three schemes, given in Figure 10. Model D will count for all the building types until the water reaches the lower level of the window opening (Figure 12 and Table 8).

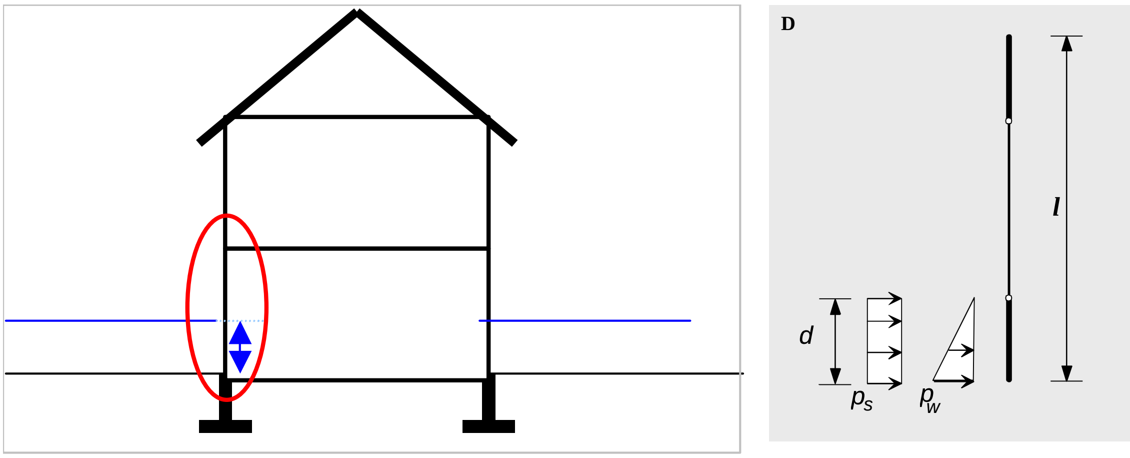

Figure 12 Load case 1”hydrostatic pressure”

	Before 1905	1905-1944	1945-1974	1975-1994	1995-2002
Floor height (m)	3.3	3.2	3.1	3	2.9
Lower level of window openings (m)	1	0.8	0.8	0.7	1

Table 8 Lower level of window openings and floor heights (l)

At the same time the velocity of the water will also apply a hydrodynamic pressure to the wall. Therefore the total force, *ΣF (N)*, will be the sum of the hydrostatic and hydrodynamic force.

$$\Sigma F = F_s + F_w \quad (3)$$

The hydrostatic pressure, p_w *(N/m)*, and the hydrostatic force per unit of length, F_w *(N)*, can be calculated as:

$$p_w = \rho g d \quad (4)$$

$$F_w = \tfrac{1}{2} p_w d \quad (5)$$

The hydrodynamic pressure, p_s *(N/m)*, and the hydrodynamic force per unit of length, F_s *(N)*, can be calculated as:

$$p_s = \tfrac{1}{2} C_D \rho v^2 \quad (6)$$

$$F_s = p_s d \quad (7)$$

In which:

ρ = density of water (1000 kg/m^3)
g = acceleration of gravity (9,81 m/s^2)
d = depth of water (m)
C_D = drag-coefficient (between 0 and 2, in this case 0,8[2])
v = water velocity (m/s)

The point of application of the total force can be calculated from equation 8.

$$x_{zwp} = \frac{F_s x_{zwp1} + F_w x_{zwp2}}{\Sigma F} \quad (8)$$

In which:

x_{zwp1} point of application of hydrodynamic force ($x_{zwp1} = \frac{d}{3}$) (m)

x_{zwp2} point of application of hydrostatic force ($x_{zwp2} = \frac{d}{2}$) (m)

The applied bending moments and shear forces has been calculated from basic mechanics equations as given in Table 9.

[2] NEN 6702 (for wind)

	Applied loads	
	Shear forces	Bending moments
Model D	$R_A = F$	$M_{\max} = Fx_{zwp}$

R_A = shear force in joint A, M_{max} = maximum bending moment

Table 9 Equations applied moments and shear forces by load case 1

3.4.2.3 Velocity of the incoming water

After equalization of the water level inside and outside the house only the hydrodynamic pressure will be applied to the walls (Figure 13). The hydrodynamic force can be calculated by equation 7 and subsequently the applied bending moments and shear forces can be calculated from basic mechanics equations as given in Table 10.

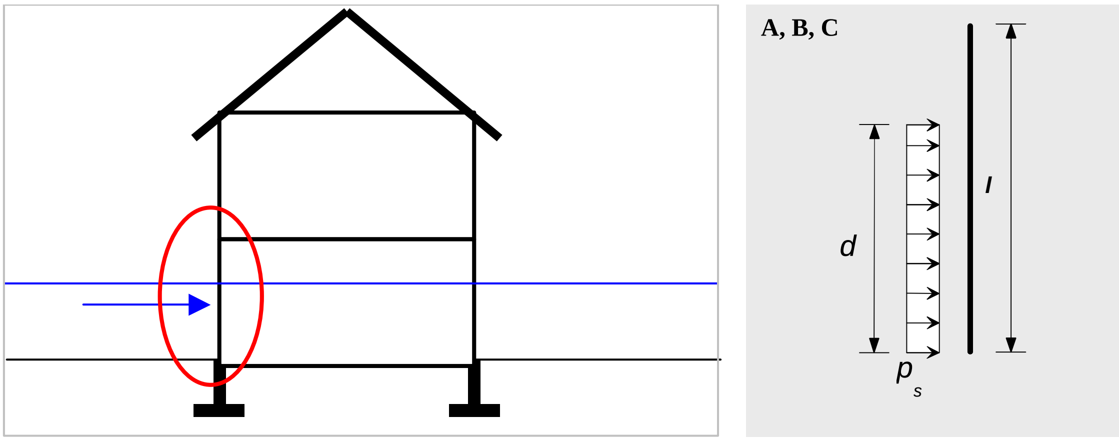

Figure 13 Load case 2 "velocity of the incoming water"

	Applied loads	
	Shear forces	Bending moments
Model A	$R_A = \Sigma F \frac{(l - x_{zwp2})}{l}$ $R_B = \Sigma F \frac{x_{zwp2}}{l}$	$M_A = 0$ $M_{\max} = \sum F x_{zwp2} \left(\frac{l - x_{zwp2}}{l} \right)^2$
Model B	$R_A = \frac{\sum F}{4l^2} \left(12(l - x_{zwp2})^2 - \frac{8(l - x_{zwp2})^3}{l} + \frac{d^3}{l} - d^2 \right)$ $R_B = \sum F - R_A$	$M_A = \frac{p_s}{l^2} \left(\frac{l^2 d^2}{2} - \frac{2ld^3}{3} + \frac{d^4}{4} \right)$ $M_V = -M_A + R_A x_0 - \frac{1}{2} \sum F \frac{x_0^2}{d}$ Where $x_0 = \frac{R_A d}{\sum F}$

	Applied loads	
	Shear forces	Bending moments
Model C	$R_A = \Sigma F\left(-\frac{(l-x_{zwp2})^3}{2l^3}+\frac{3(l-x_{zwp2})}{2l}\right)$ $R_B = \Sigma F - R_A$	$M_A = \frac{p_s}{8l^2}\left(l^2-(l-x_{zwp2})^2\right)^2$ $M_V = -M_A + R_A x_0 - \frac{1}{2}\sum F\,\frac{x_0^2}{d}$ Where $x_0 = \frac{R_A d}{\sum F}$

R_A = shear force in joint A, R_B = shear force in joint B, M_A = Bending moment in joint A, M_V = bending moment at point in structure where R is equal to zero

Table 10 Equations applied moments and shear forces by load case 2

3.4.2.4 Wave action

After the area is flooded it is assumed that the velocity of the water reduces to zero. Depending on the water level and the wind velocity it is possible that waves will arise. Therefore the significant wave heights, H_s, have been calculated based on the following assumptions:

- the maximum water level has been reached in the first ten hours. For each geographical unit (postal code area) this maximum water level has been calculated
- the wind force is equal to the wind force which is exceeded 5% of the time and is based on the omni-directional distribution of probability for the wind force measured at Schiphol: this gives a wind velocity of 14 m/s
- a fetch length of 100 meters (building density > 15 buildings per hectare) and 1000 meters (building density < 15 buildings per hectare)

The calculation of the loads (per unit of length) by waves, F_g *(N)*, is based on the significant height of waves as follows:

$$p_g = (H_s + 0{,}5H_s)\rho g \quad (9)$$

$$F_g = p_g H_s \quad (10)$$

In which:

p_g = wave pressure (N/m²)
H_s = calculated significant height of wave (m)
ρ = density of water (1000 kg/m³)
g = acceleration of gravity (9,81 m/s²)

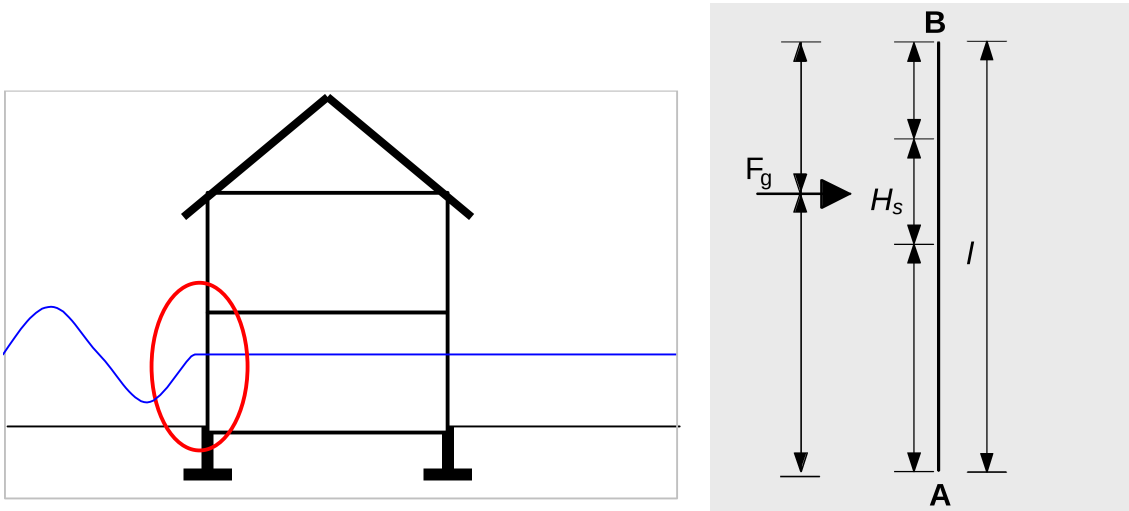

Figure 14 Load case 3 "wave action"

The point of application, x_{zwp} *(m)*, can be calculated from equation 11.

$$x_{zwp} = d + \frac{H_s}{2} \tag{11}$$

The applied bending moments and shear forces can than be calculated from the basic structural mechanics equations given in Table 11.

	Applied loads	
	Shear forces	Bending moments
Model A	$R_A = \sum F \frac{(l - x_{zwp})}{l}$ $R_B = \Sigma F \frac{x_{zwp}}{l}$	$M_A = 0$ $M_{\max} = \sum F \cdot \frac{(l - x_{zwp})x_{zwp}}{l}$
Model B	$R_A = \frac{\Sigma F (l - x_{zwp})^2}{l^3}(3x_{zwp} + (l - x_{zwp}))$ $R_B = \sum F \frac{x_{zwp}^2}{l}(3 \cdot (l - x_{zwp}) + x_{zwp})$	$M_A = \sum F \cdot x_{zwp}\left(\frac{l - x_{zwp}}{l}\right)^2$ $M_V = -(M_A - R_A \cdot x_{zwp})$
Model C	$R_A = \Sigma F\left(-\frac{(l - x_{zwp})^3}{2l^3} + \frac{3(l - x_{zwp})}{2l}\right)$ $R_B = \sum F - R_A$	$M_A = \sum F \frac{(l - x_{zwp})(l^2 - (l - x_{zwp})^2)}{2l^2}$ $M_V = -(M_A - R_A \cdot x_{zwp})$

R_A = shear force in joint A, R_B = shear force in joint B, M_A = Bending moment in joint A, M_V = bending moment at point in structure where R is equal to zero

Table 11 Equations applied moments and shear forces by load case 3

3.4.2.5 Debris

The occurrence of floating debris outside the house, which may strike walls, depends on the water depth and the weight of the debris. It is supposed that in any case some debris will start floating at a water depth of half a meter or more and strike into the walls. The speed of the debris crashing into the walls is assumed equal to the water velocity calculated by Delft FLS. The applied force, F_d *(N)*, on the structures due to this crashing can than be calculated as follows:

$$F_d = v\sqrt{mk_t} \qquad (12)$$

In which:

v = velocity of flow (m/s)
m = weight of debris (50 kg)
k_t = spring stiffness ($\frac{1}{k_t} = \frac{1}{k_w} + \frac{1}{k_d}$ N/m)
k_w = spring stiffness of wall (N/m)
k_d = spring stiffness of debris (N/m)

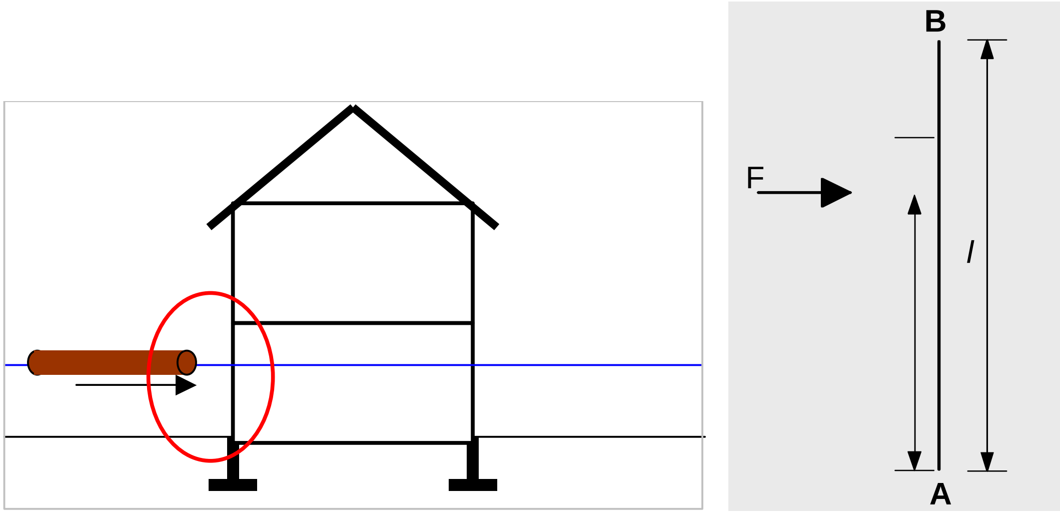

Figure 15 Load case 3

In this case a piece of wood has been taken as example of the debris which may bump into the wall. The dimensions have been set on 1,5*0,2*0,2 m and the weight on 50 kg (approximate density ρ = 900 kg/m^3). The spring stiffness of the wood can be calculated from equation 13 and the spring stiffness of the walls by standard mechanics equations (Table 12). The used Young's modulus, *E (Pa)*, and moment of inertia, *I (m^4)*, for the different structures are given in Table 13.

$$k_d = \frac{E_d A_d}{l_d} \qquad (13)$$

In which:

E_d = Young's modulus of debris (Pa)
A_d = surface area of debris (m^2)
l_d = length of debris (m)

	Applied loads
Model A	$k_w = \frac{27 \cdot EI \cdot l}{d(l-d)\left((d+2(l-d))\sqrt{3d(d+2(l-d))}\right)}$
Model B	$k_w = \frac{3EI \cdot (3d+(l-d))^2}{2d^3(l-d)^2}$
Model C	$k_w = \frac{4EI \cdot l^2}{(l-d)^2 d^3 \cdot \left(1+\frac{l-d}{3l}\right)}$

Table 12 Equations spring stiffness of wall

Type of structure	*Young's modulus*	*Moment of inertia*	*ref.*
Brick (TB1 and TB2)	$1.5*10^9$ Pa	$I = \frac{1}{12} w t_w^3$	Waarts, 1997
Concrete (CC and PF)	$28*10^9$ Pa		Vrouwenvelder et al. 1987
Debris (wood)	$9*10^9$ Pa	-	Adan

Table 13 Young's modulus and Moment of inertia

Subsequently the applied bending moments and shear forces can be calculated from the equations given in Table 11.

Figure 16 Floating debris during the flood of February 1953 in the Netherlands (Boon, 1916)

3.4.2.6 Strength of the structures

The input for calculating the strength of the structures is related to the building data. This data provides, for instance, information about materials used and number of floors. For calculating the strength of the structures first the normal forces will be calculated, for each building. Subsequently the bearing capacity in terms of moments and shear forces can be calculated for each structure by using the corresponding material properties.

The normal force per unit length is calculated as follows:

$$N_d = \left(\left(q_{sw,fl} + q_{sl} + q_w y_w\right)\alpha_{floor} dr + q_{sw,wl}\, l\right)n + \left(q_{sw,rf} + q_d y_d\right)\alpha_{roof} dw \qquad (14)$$

In which:

N_d	Normal force (kN)
$q_{sw,fl}$, $q_{sw,wl}$, $q_{sw,rf}$	Self weight floors, walls, roof (kN/m^2)
q_{sl}	Surface load (kN/m^2)
q_w, q_d	Live load residential parts, roofs (kN/m^2)
γ_w, γ_d	Load factors (-)
α_{floor}, α_{roof}	geometrical factor floor, roof (m)
d_r	mean depth of room behind the wall (m)
d_w	mean depth of building (m)
l	height of floor (m)
n	number of floors (-)

The last term of equation 14 is optional in case of a saddle roof (Table 15). For each building the live load of residential parts, q_w, is equal to 0,3 kN/m^2 and of roofs, q_d, 0 kN/m^2. The corresponding load factors, γ_w and γ_d, are respectively 1 and 0 (Vrouwenvelder et al., 1987).

In Table 14, Table 15, Table 16, properties are given for, respectively, the different structures (NEN 6702; Adan, 1994), building types and ranges of date of construction.

			TB	*TB2*	*CC*	*PF*
Floors			timber	concrete	concrete	concrete
Density	ρ_f	kg/m^3		2400	2400	2400
Thickness	t_f	m		0.2	0.2	0.08
Self weight	$q_{sw,fl}$	kN/m^2	0.65	4.8	4.8	1.92
Surface load	q_{sl}	kN/m^2		0.5	0.5	0.5
Walls			masonry	masonry	concrete	concrete
Density	ρ_w	kg/m^3	1800	1800	2400	2400
Wall thickness	t_w	m	0.22	0.22	0.15	0.08
Self weight	$q_{sw,wl}$	kN/m^2	3.96	3.96	3.6	1.92
Roof construction	$q_{sw,rf}$	kN/m^2	0.7	0.7	0.7	0.7
Geometrical data	α_{roof}^{*}		0.5	0.5	0.5	0.25
	α_{floor}^{**}		0.5	0.25	0.5	0.25

* 0,5 roof loads carried down by relevant wall; 0 not load bearing
** 0,5 floors span in 1 direction; 0.25 span in two directions; 0 not load bearing

Table 14 Properties of each type of structures

Building type	*Number of floors*	*Saddle roof*	*Depth of room (d_r)*	*Depth of building (d_w)*
Single family dwelling, 1 floor	1	Yes	10	10
Single family dwelling, 2 floors	2	Yes	10	10
Single family dwelling, > 2 floors	3	No	10	10
Houses with a porch	3	No	5	8
Gallery flats	6	No	5	8
Maisonnettes	4	No	5	8
Other more family dwellings	3	No	5	8

Table 15 Properties for each building type

	Before 1905	1905-1944	1945-1974	1975-1994	1995-2002
Height of floor	3.3	3.2	3.1	3	2.9
Lower level of window opening	1	0.8	0.8	0.7	1

Table 16 Height of floor in meters for each range of date of construction

3.4.2.7 Brick structures

The compressive stress, σ_c, and shear strength, f_v, of the structures, that are built in brick (TB and TB2), has been calculated using equation 15 and 16. Subsequently the capacity in terms of bending moments and shear forces has been calculated by the equations given in Table 17.

$$\sigma_c = \frac{N_d}{w * t_w} \tag{15}$$

$$f_v = 0{,}5 f_t + 0{,}5\sigma_c \tag{16}$$

In which:

σ_c	= compressive stress (N/mm^2)
w	= width (m)
t_w	= thickness wall (m)
f_v	= shear strength (N/mm^2)
f_t	= tensile strength (in this case 0,28 N/mm^2)[3]

Type of structure	Bending moments	Shear forces
TB	$M_u = (f_t + \sigma_c) \frac{1}{6} w t_w^2$	$V_u = f_v w t_w$
TB2	$M_u = (f_t + \sigma_c)\left(\frac{2}{6} w t_w^2\right)$	$V_u = f_v w 2 t_w$

Table 17 Equations bearing capacity masonry structures

3.4.2.8 Concrete structures

The capacity in terms of bending moments and shear forces of the structures built in concrete (CC and PF) has been calculated as follows. For calculating the capacity in terms of moments the compressive zone height is calculated as given by equation 17. For calculating the shear forces the shear stress is calculated. This has been carried out by using equation 20 as given in NEN 6720.

$$x_u = \frac{N_d + N_s}{\frac{3}{4} f_{b,gem,upgr}} \tag{17}$$

Where:

$$N_s = (\omega_o t_u w) f_s \tag{18}$$

Where:

$$t_u = t_w - c - \frac{\phi_k}{2} \tag{19}$$

In which:

x_u	= compressive zone height (mm)
N_d	= normal force (N)
N_s	= force in concrete steel (N)
$f'_{b,\,gem,\,upgr}$	= compressive strength concrete (N/mm^2)
ω_o	= reinforcement percentage (in this case set on 60%)
t_u	= useful thickness of wall (mm)
f_s	= tensile strength steel (N/mm^2) see Table 18
c	= cover on reinforcement (mm) see Table 18
ϕ_k	= mean diameter of steel bars (in this case set on 10 mm)

[3] Waarts, 1997

$$\tau = 0.4(1.05 + 0.05 f_{b,gem,upgr}) + \frac{0.15 N_d}{t_w w} \tag{20}$$

In which:

τ = shear stress (N/mm²)

t_w = thickness wall (mm)

The concrete parameters given in Table 18 are based on an expert's opinion. The parameters are all reasoned out from the standard parameters, which were applicable in the different time periods. For the compressive strength, $f'_{b,gem}$ these parameters have been multiplied with an upgrade factor, since the compressive strength of concrete increases in time.

Properties	Before 1905	1905-1944	1945-1974	1975-1994	1995-2002
$f'_{b,gem}$ (N/mm²)	18	20.5	23	28	33
upgrade factor	2.5	2.5	2	1.7	1.4
$f'_{b,gem,upgr}$ (N/mm²)	45	51.3	46	47.6	46.2
f_s (N/mm²)	240	240	360	500	500
c (mm)	15	15	17	25	25

Table 18 Properties concrete

Type of structure	Bending moments	Shear forces
CC & PF	$M_u = N_d\left(t_w/2 - 7/18\, x_u\right) + N_s\left(t_u - 7/18\, x_u\right)$	$V_u = (\tau \cdot t_w w)$

Table 19 Equations capacity concrete structures

3.5 Output

The output of the model consists of the percentage of partial collapsed (e.g. collapse of one load bearing wall or scour of foundation) buildings due to the failure mechanisms, failure of walls and scour of the foundation. It is expected that 70% of the partial collapsed buildings will collapse totally. Before discussing the total damage, the mechanisms will first be discussed separately.

3.5.1 Scour of the foundation

In 69% of the postal codes no damage will occur in the first six hours of the flood, due to scour of the foundation. In 31% of the postal codes less then 5% of the buildings will be partial damaged in the first six hours of the flood (see Figure 17). In these postal codes areas the maximum water velocity exceeded the water velocities given in Table 6 as a result of what the buildings, which were built on shallow foundations, were partial damaged.

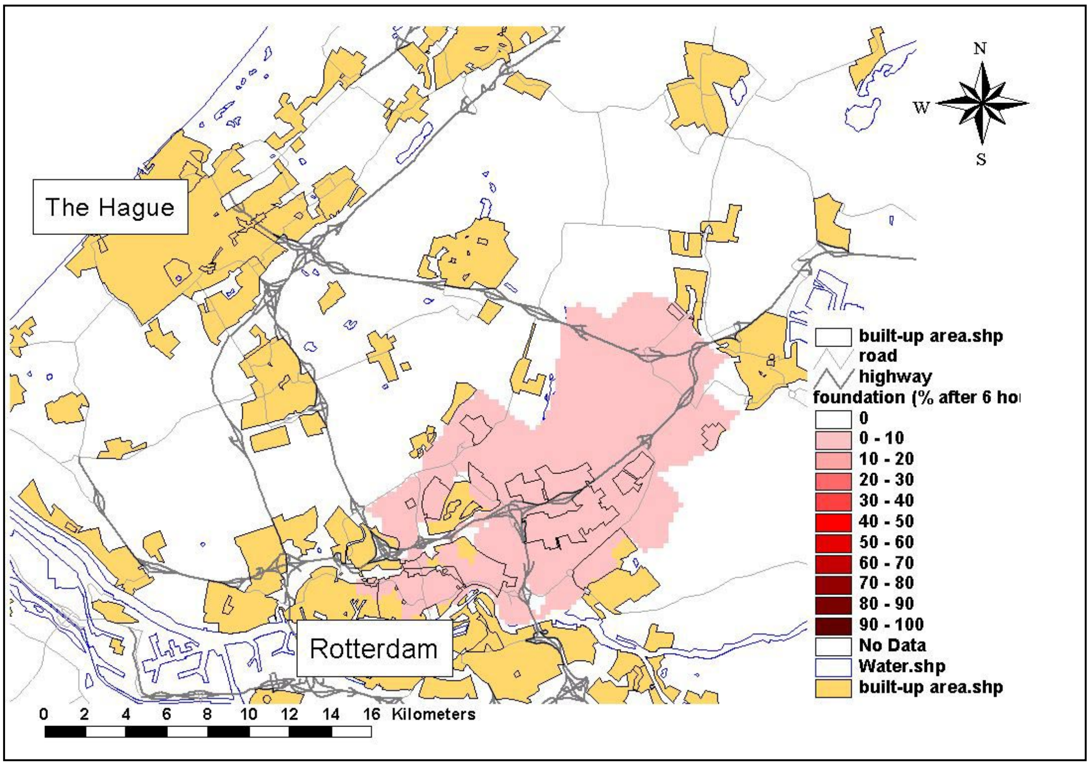

Figure 17 Percentage partial collapse by scour of the foundation after six hours

3.5.2 Failure of walls

The output for the case “Midden Holland” of the mechanism failure of walls shows that in 72% of the flooded postal codes no structural damage will occur due to the flood in the first six hours. In 16% of the flooded postal codes more then 5% of the buildings will be partial damaged (see Figure 18). This implies that in these cases for some buildings the applied bending moments or shear forces exceed the strength in terms of bending moments or shear forces.

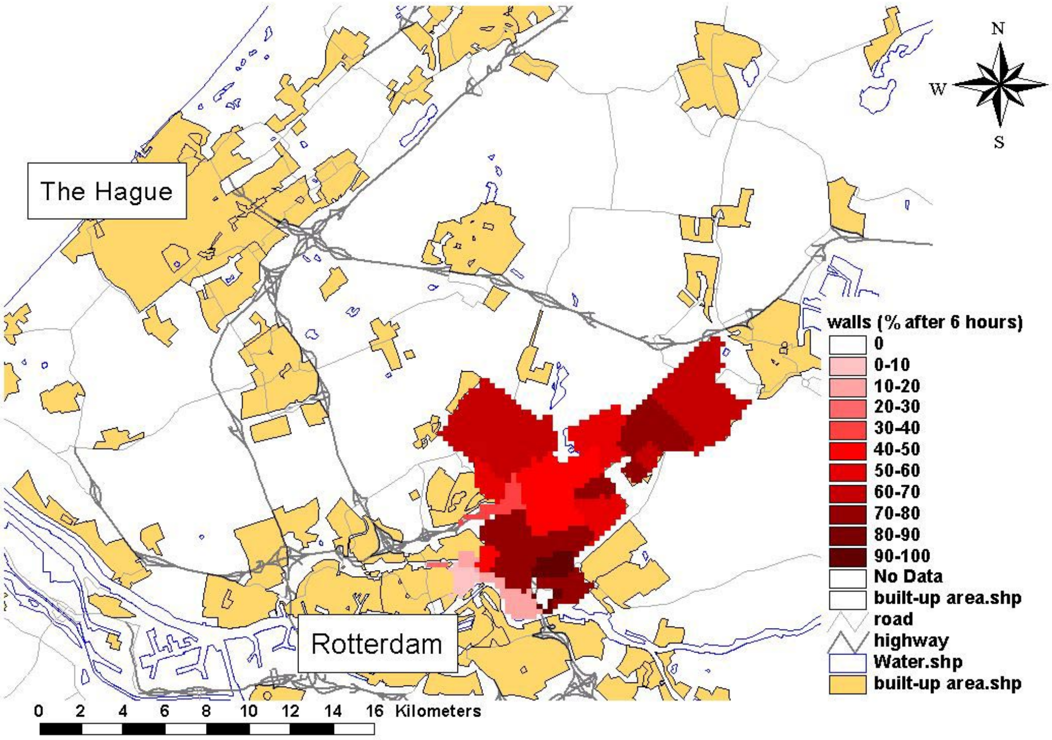

Figure 18 Percentage partial collapse by failure of walls after six hours

To illustrate the moment that partial damage will start to occur, "velocity – depth" damage curves have been generated from the model for each load case and for the total mechanism, failure of walls in the following paragraphs. In these damage curves this moment is indicated by a coloured continuous line for each distinguished type of structure.

First the damage curves for each load case will be discussed and subsequently the damage curve for the total mechanism. All the damage curves are determined within the range for water velocities and water depths given by the case "Midden Holland" (respectively 0.0 – 3.2 m/s and 0.0 – 4.9 m).

3.5.2.1 Hydrostatic pressure and hydrodynamic pressure

The damage curve for load case 1 "Hydrostatic pressure" has been combined with load case 2 "Velocity of the incoming water" (see Figure 19). As can be seen from these curves the structures made from cast concrete (CC) and prefabricated concrete (PF) will not be damaged within the given ranges for water velocity and water depth. The structure type "traditional way of building 2", (TB2) is the most sensitive for this load case because the applied bending moments exceed the strength of the structure in terms of bending moments. From this damage curve can be concluded that the wall thickness (the only difference between TB and TB2) plays an essential part in the strength of masonry structures.

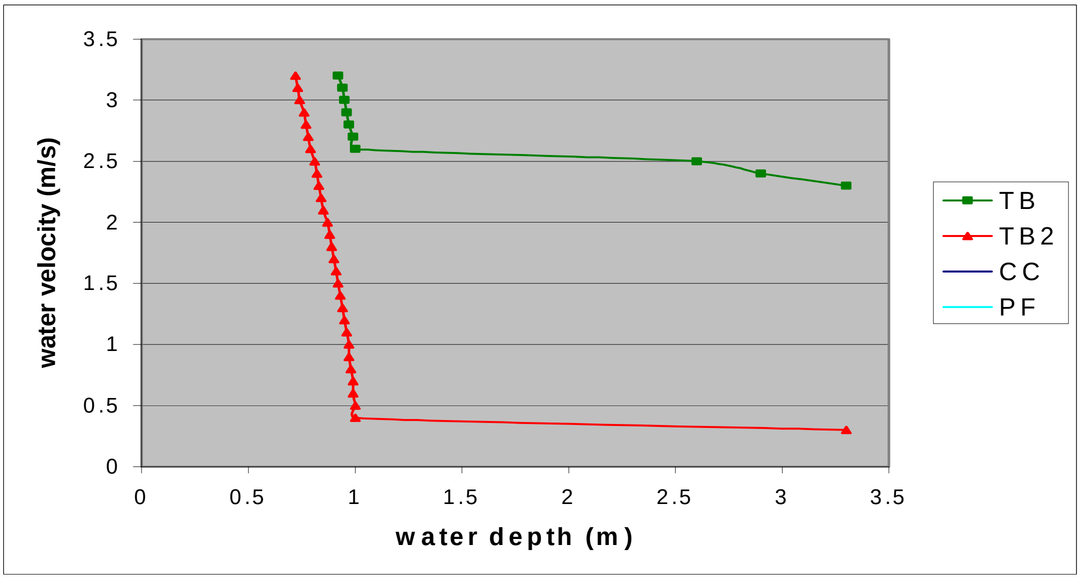

Figure 19 Damage curve "hydrostatic and hydrodynamic pressure"

3.5.2.2 Wave action

Within the given range of water depths, a wind force of 14 m/s and a fetch length of 100 or 1000 meters, wave action will not create any structural damage. Therefore no damage curve has been made for this load case.

3.5.2.3 Debris

The damage curves for debris are shown in Figure 20. The courses of these damage curves are rather complex. This complexity is due to the fact that failure on bending moment and failure on shear forces is combined in one curve. To illustrate this, the curve of cast concrete has been split up for failure on bending moment and shear forces (see Figure 21).

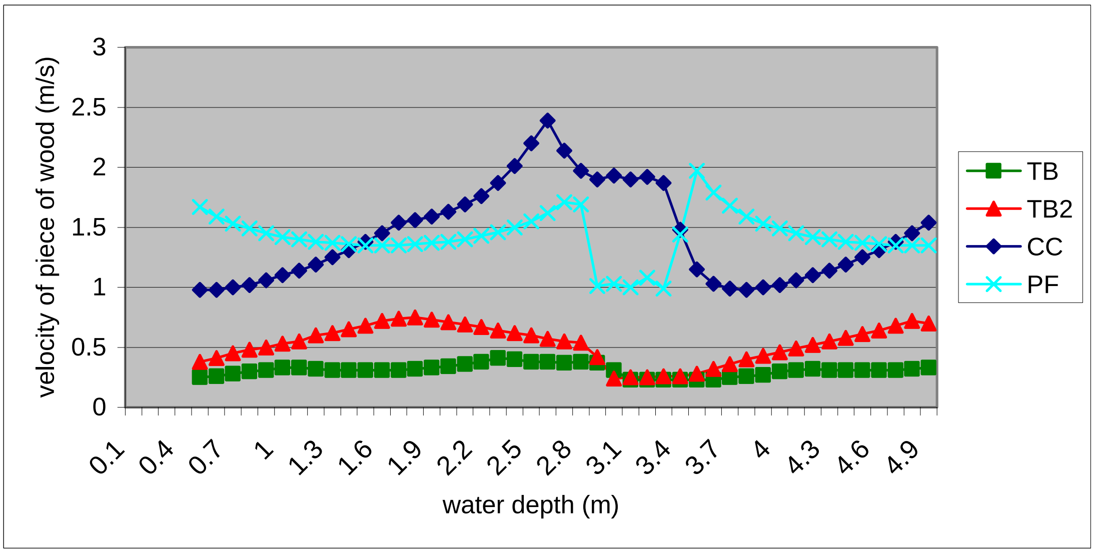

Figure 20 Damage curve " debris"

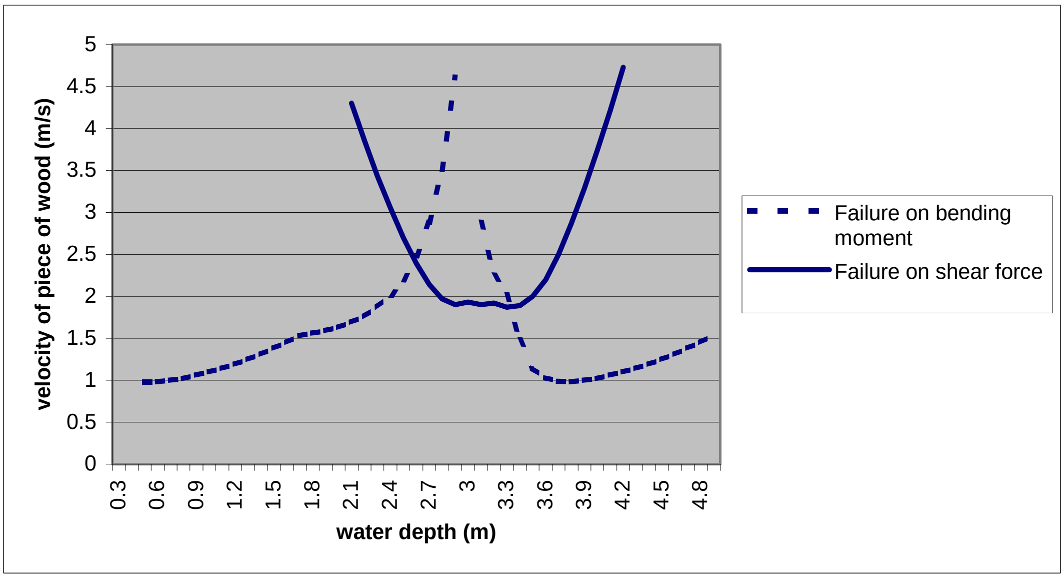

Figure 21 Structural failure for cast concrete (CC)

Failure on bending moment

The curve given in Figure 21 for failure on bending moment is a combination of two curves, because the applied bending moment has been calculated for two points in the wall (joint A (M_A) and the point of application (M_V)) as can be seen in Figure 22. Therefore the curve for failure on bending moment in Figure 21 contains a kink at a water depth of approximately 1.8 meters, as an example. In Figure 22 the two curves of applied bending moments are given for a single family dwelling of 1 floor, which is constructed before 1905 (the water velocity is fixed on 1.0 m/s).

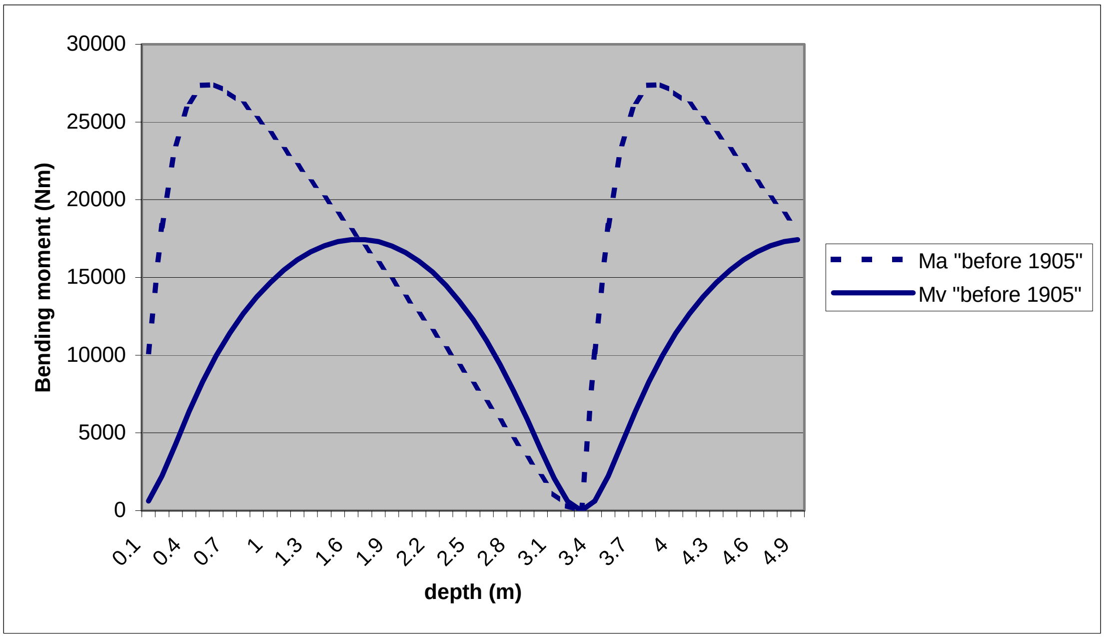

Figure 22 Curve of bending moment

In Figure 23 the combined curve for bending moment is given for several velocities. The line “Max” gives the strength of the structure. Failure will occur if the applied bending moment exceeds this line. This implies that failure on bending moment will occur from velocities of approximately 1.0 m/s (see also Figure 20).

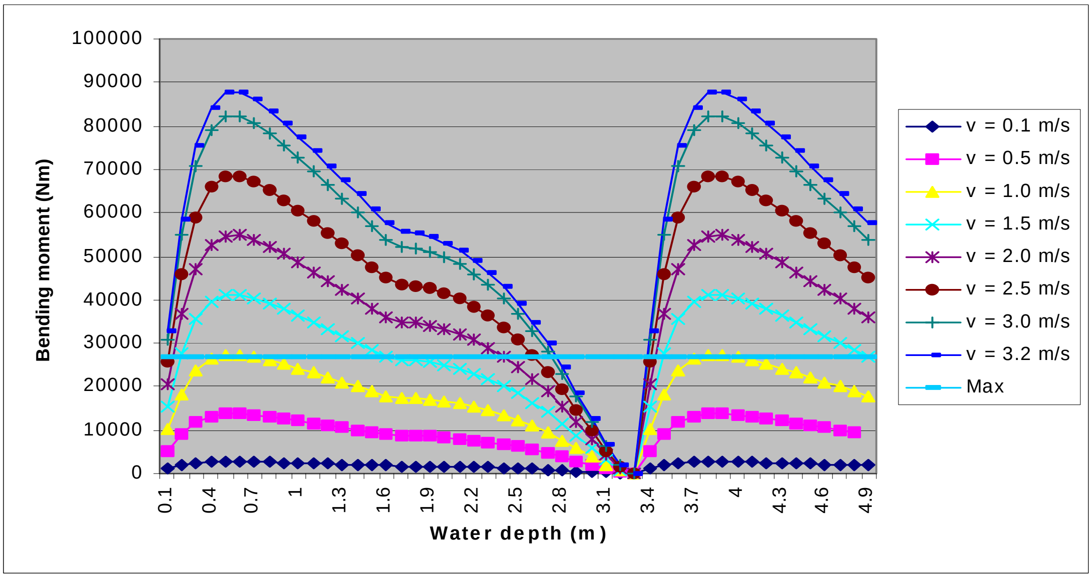

Figure 23 Curves of bending moment for several water velocities

Failure on shear force
Subsequently in Figure 24 the curve for shear force (R_{max}) for the same building type and date of construction is given. The curve has also been given for several water velocities within the range 0.0 to 3.2 m/s. This shows that strength line "Max" will be exceeded if the velocity is more than approximately 2.0 m/s.

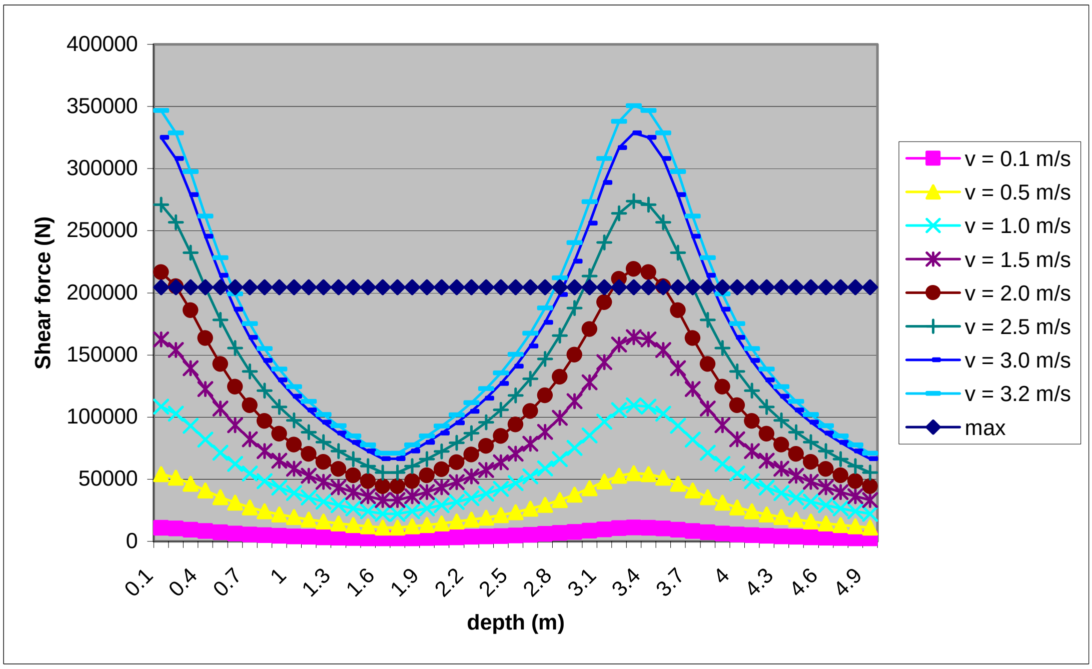

Figure 24 Curve of shear force for several water velocities

The curves given in Figure 23 and Figure 24 are based on data of a certain building type (single family dwelling with one floor) and date of construction (before 1905). The total curve given in Figure 20 consists of a combination of these two curves for each building type and date of construction.

3.5.2.4 Damage curve failure mechanism “failure of walls”

In Figure 25 the damage curve has been given for the failure mechanism “failure of walls”. The damage curve is almost equal to the damage curve given for load case 4, “debris”, in paragraph 3.5.2.3. In this case debris is the determining load case for failure of walls. In Figure 26 the curves indicate the moment that the walls of all buildings of a certain type of structure will fail.

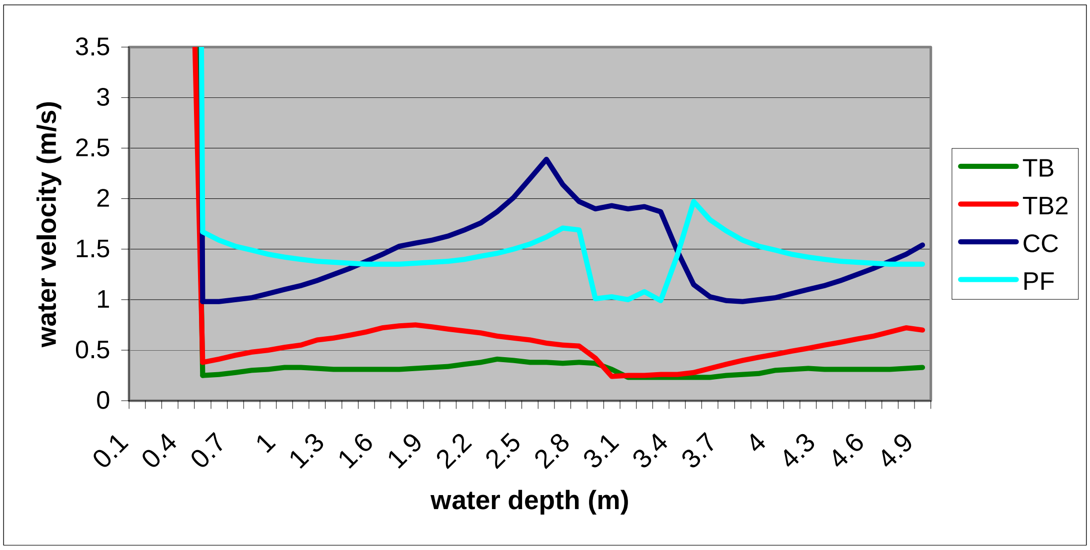

Figure 25 Damage curve “start failure of walls”

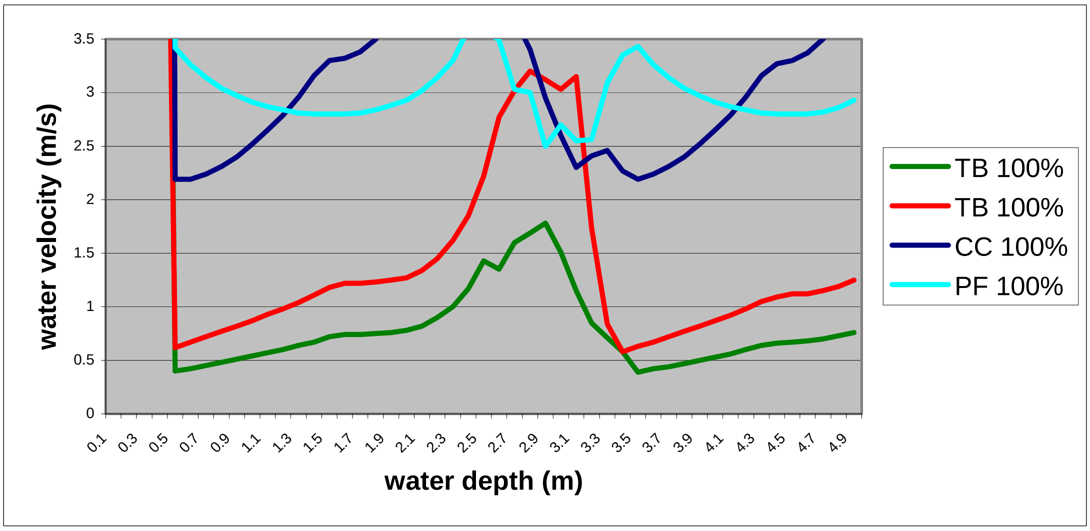

Figure 26 Damage curve “100% failure of walls”

4 Uncertainties

Due to uncertainties in the input data the output will be uncertain as well. Therefore the uncertainties in the input data will be discussed below.

Building factors
The building factors are taken from different databases, which have been coupled to generate all the needed information for the model. This conversion caused some uncertainties.
The building types, which are presented in both databases, did not match. Therefore a conversion has been made. Both databases do not provide definitions for the building types they use. Therefore misinterpretations are possible.

- The MEB database provides stock numbers that are not related to geographical units. These stock numbers have been translated in percentages. The percentages therefore are reflecting a situation, which applies for the Netherlands in general. This means that the output of Bridgis, which is related to geographical units, will be converted with data, which applies for the Netherlands in general. Therefore it could be, for example, that ten houses found by Bridgis in the Noordoostpolder (built on since 1942) will be converted into 10 houses, which are built before 1905. Refining the Bridgis data can reduce this uncertainty. In this study Bridgis consist of building type related to geographical units but it is also possible to relate this data to the date of construction. This way the conversion can be made more accurate.

Flood factors
The flood factors has been predicted for specific time intervals. In this case the time interval have been set on one hour. This may cause uncertainties in the magnitude of the loads caused by the flood data because the maximums can be missed. For example in this case the water depth and water velocity are used which are present on exact one, two, three, four, five and six hours after the dike breach. The water depths and velocities present at these point in time may not include the maximum water velocity and depth which are responsible for higher loads on the buildings. For a more accurate calculation the maximum water velocity and corresponding water depth and the maximum water depth and the corresponding water velocity should be distracted from the output of the hydraulic model.

Other factors
Most of the mentioned “other factors” in paragraph 3.3.3 have not been taken into account in the model. These factors are all subject to the location of the building, therefore no data was available about these factors which could be linked to geographical units. By using data in general more uncertainties might be caused.

Load cases

- The amount of debris (furniture inside the house included) in the water depends on the possibility of matter to be carried away by the water. It’s impossible to make a quantification of this amount related to geographical units, therefore it is supposed that in any case debris will strike walls. A mean weight for the debris has been assumed on 50 kg and the velocity of the debris has been assumed et equal to the water velocity. These two assumptions will cause uncertainties in the output.
- Due to the fact that load case “debris” dictates the damage curve for the whole model it is important to define the used parameters for this load case more accurate.
- In this study it is assumed that the walls are at right angles to the water. In practice this is not the case. Therefore the calculations for the failure of walls mechanism might result in more collapsed buildings than if the actual orientations of all the buildings would be taken into account. This could be made more accurate if the C factor mentioned in equation 3 has been determined.

- It is supposed that the walls to which to the loads are subjected are not supported by partition walls, which are in right angles with the wall. This simplification makes it possible to use 2D calculations.
- The decrease of the load on the structure due to protection by objects upstream has not been taken into account in the model (except for wave action). Consequently the results of the calculations may result in more damaged buildings due to the overestimated water velocity.

5 Conclusions

The output of the total model after six hours is given in Figure 27. From this figure can be concluded that the percentage of partial damaged buildings increases near the breach. Near breaches the velocity will be high. High velocities (> 2,0 m/s) together with a depth more than 0,5 meter will result in partial damaged buildings of each kind of structure (see Figure 25). The average water depth in case of a dyke breach near Krimpen is 1.67 meters. As can be seen in Figure 25 this will already cause damage to some of the masonry structures if the velocity is more than 0,3 m/s. At approximately 16 kilometers from the breach no damage will occur.

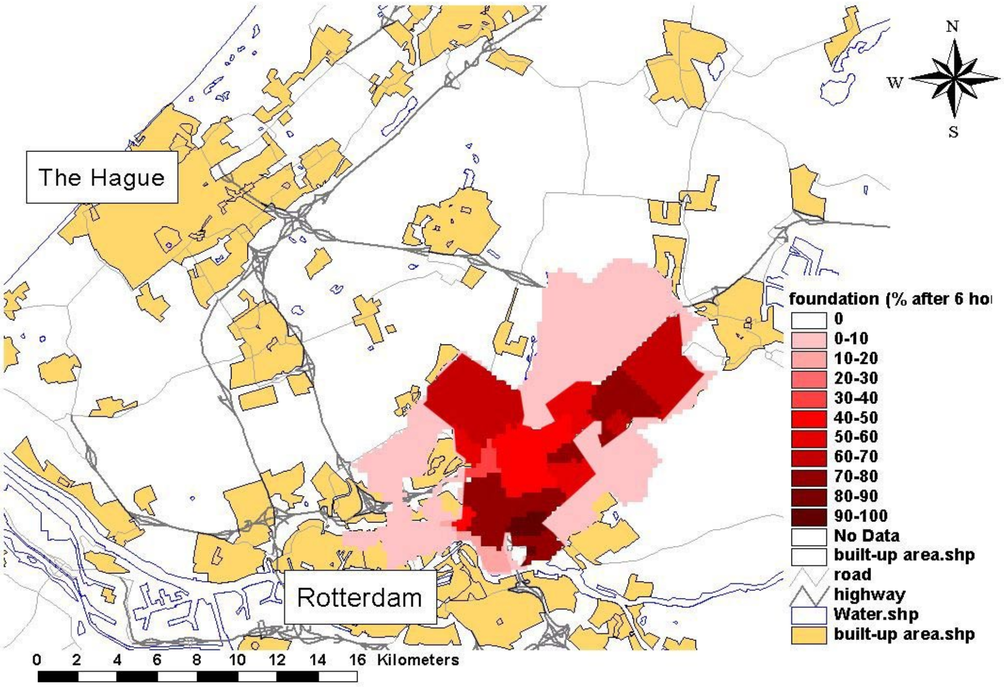

Figure 27 Percentage of partly collapse by the two mechanisms

It appears that from the failure mechanisms investigated in this study, the failure mechanism “failure of walls” will cause the most damage. Damage by scour of the foundation is only a fraction of damage caused by the failure of walls. The loads applied to the walls by debris appears to be the most damaging. Wave action does not cause damage at all and the loads due to water velocity and water depth have less impact on the structures than debris. Therefore the damage curve for the failure mechanism “failure of walls” is totally dictated by the damage curve given by the load case “debris”.

The damage curves (see Figure 25 and Figure 26) show that there is no linear correlation between the water velocity and the water depth for damage. A linear correlation was however given in the study by Clausen et al., 1990 and also used in the RESCDAM project.

It is recommended to minimize the uncertainties, which are given in the previous chapter. Especially the uncertainties in load case “debris” should be minimized, since this load case dictates the amount of damage calculated by the model.

6 References

Adan, O.C.G. 1994. *Eigenschappen van bouw- en isolatiematerialen* Stichting Bouw Research

Allewijn, R. 1983. *Een zee van water Februarivloed 1953 over de Hoeksche Waard en het Eiland van DordrechtWaterschap* 'De Groote Waard', Klaaswaal

Black, R. *"Flood proofing rural residences";* a project 'Agnes' report, no EDA 77-088, US Dept of Commerce, EDA 1975

Boon, N.J. 1916 *Herinnerings-album van den Grooten Watersnood van Januari 1916* Amsterdam

Clausen, L. and Clark, P.B. *"The development of criteria for predicting dambreak food damages using modeling of historical dam failures";* International conference on river flood hydraulics, 1990

Kelman, I. 2002 *Physical flood vulnerability of residential properties in coastal, eastern England* Dissertation University of Cambridge, UK

Mijala, T. 2001 *Development of Rescue Actions Based on Dam-Break Flood Analysis* RESCDAM Final report

Molenaar, D.J. and Vrouwenvelder, A.C.W.M. *Modellen voor de bepaling van directe schade* Syllabus "Wat als we nat gaan", 02.02.02

Polder, R.B. and Bijen, J.M.J.M *"Corrosie van wapening en andere metalen in beton";* Corrosie en corrosiebestrijding 8, Nederlands Corrosie Centrum, Bilthoven

Reimer, N. 2002 *Als der Regen kam, ein Fotolesebuch zur flut in Sachsen* Michel Sandstein Verlag, Dresden

RESCDAM, *"Development of rescue actions based on dam-break flood analysis"*, final report, June 1999 – March 2001

TGB Belastingen en vervormingen NEN 6702

Waarts, P.H., *Kans op schade aan bouwwerken door trillingen* TNO Rapport 97-CON-1698, 1997

Vrisou van Eck, N., Kok, M., Vrouwenvelder, A.C.W.M. 1999. *Standaardmethode Schade en Slachtoffers als gevolg van overstromingen* RWS Dienst Weg- en Waterbouw

Vrouwenveld, A.C.W.M., Siemes, A.J.M. 1987. *Probabilistic calibration procedure for the derivation of partial safety factors for the Netherlands building codes* Heron Volume 32, no 4

Vrouwenvelder, A.C.W.M and Waarts, P.H. *"TAW-E rapport Risico Analyse";* TNO rapport 94-CON-R0120, januari 1994

General Appendix: Delft Cluster Research Programme Information

This publication is a result of the Delft Cluster research-program 1999-2002 (ICES-KIS-II), that consists of 7 research themes:
►Soil and structures, ►Risks due to flooding, ►Coast and river , ►Urban infrastructure, ►Subsurface management, ►Integrated water resources management, ►Knowledge management.

This publication is part of:

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Baseproject name	:	Consequences of floods		
Project name	:	Consequences of floods		
Projectleader/Institute		Prof. A.C.W.M. Vrouwenvelder		TNO
Project number	:	02.03.03		
Projectduration	:	01-02-2002	-	1-07-2003
Financial sponsor(s)	:	Delft Cluster		
		Ministry of Public Works, Road and Water Management		
		GeoDelft		
		WL|Delft Hydraulics		
		TNO		
		Delft University of Techonology		
Projectparticipants	:	Twente University		
		Alterra		
		CSO		
		Delphiro		
Total Project-budget	:	€ 450.000		
Number of involved PhD-students	:	2		
Number of involved PostDocs	:	0		

Delft Cluster is an open knowledge network of five Delft-based institutes for long-term fundamental strategic research focussed on the sustainable development of densely populated delta areas.

Keverling Buismanweg 4
Postbus 69
2600 AB Delft
The Netherlands

Tel: +31-15-269 37 93
Fax: +31-15-269 37 99
info@delftcluster.nl
www.delftcluster.nl

Theme Managementteam: Ground and Construction

Name	**Organisation**
Prof. J.K. Vrijling	Delft University of Technology
Ir. E.O.F. Calle	GeoDelft
Prof. A.C.W.M. Vrouwenvelder	TNO

Projectgroup

During the execution of the project the researchteam included:

Name	**Organisation**
Prof. Ir. A.C.W.M. Vrouwenvelder	TNO
Dr. Ir. P.H. Waarts	TNO
Ir. J.E.A. Reinders	TNO
Dr. E.E. van der Hoek	GeoDelft
Ir. S.N. Jonkman	RWS-DWW
Ir. K. Heynert	WL | Delft Hydraulics
Prof. A. van der Veen	Twente University
Ir. L.C.P.M. Stuyt	Alterra
Ir. M. de Muinck Keizer	Delphiro/CSO

Other Involved personnel

The realisation of this report involved:

Name	**Organisation**
Ir W. Roos	TNO Bouw