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Design Studies on Flood-Proof House

Sponsored by ICE R&D Enabling Fund

November 2002

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Synopsis

The Environment Agency (EA) estimates that two million homes and businesses and five million people are at risk from flooding in England and Wales(1). Many flood experts and scientists, including members of the Environment Agency (UK) and the Federal Emergency Management Agency (USA), agree that climate change and continued urban development will increase flood frequency and severity over the next century. With widespread damage caused in 1999, 2000 and 2001, flooding is clearly a significant issue in Britain and the world. Although the EA is devoting considerable time and money to public flood defences, modest thought is given to individual residences. Our group set out to design a Flood-Proof House, or FPH, that is habitable during a flood, requires little or no input from the homeowner and, most importantly, minimises a flood's impact on the homeowner, property and the home itself.

This report chronicles a multiple step process leading to a final FPH design. Initial research into flood information, current mitigation techniques and emerging technologies produces several preliminary options. From this list, a controlled floating mechanism is chosen. In addition to qualitative analyses, some basic calculations were undertaken involving those features of the FPH that distinguish it from other residences. Detailed consideration is given to the watertight concrete basement, the foundation, the lateral restraint system and the sedimentation problem. The combination of these different components results in a technically feasible and economically acceptable design.

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1. Introduction

1.1. Project statement

A Flood-Proof House? At first, the very notion seems vague and far-fetched. However, some consideration reveals a fantastic range of possibilities. Certainly, many simple examples already exist in the form of elevated structures and houseboats. In today's technologically geared world, a more inventive alternative is well within the realm of possibility. So what exactly do a flood-proof residence mean? The main function of a Flood-Proof House, or FPH, is habitable during a flood, requires little or no input from the homeowner and, most importantly, minimises a flood's impact on the homeowner, property and the home itself. Ideally, then, the FPH should be completely impervious to water while maintaining the appearance of a traditional home. Furthermore, it should preferably apply to varying soil and flood conditions. This report explores a variety of options that could contribute to such a Flood-Proof House. In addition to qualitative analyses, some basic calculations were undertaken involving those features of the FPH that distinguish it from other residences. Our intention is to combine these elements into one unique and feasible FPH design, acceptable to the user and the environment.

1.2. Project relevance

The motivation for this project stems from current global trends in flooding. Many flood experts, including members of the Environment Agency (UK) and the Federal Emergency Management Agency (USA), agree that climate change and continued urban development will cause more frequent and severe flooding in the future. Furthermore, Britain's position as one of the most densely populated countries in Europe reinforces the need for more residential space. The project is applicable to many regions around the globe, although the design team are focusing on protecting against flood conditions common in the UK.

1.3. Objectives

At the beginning of the project, six objectives were set:

- Evaluation of recent flood damage to residential buildings in the UK and worldwide;
- Survey of current flood alleviation techniques for residential buildings;
- Survey of current and emerging technologies that may be useful towards flood-proofing;
- Design a four bedroom detached Flood-Proof House;
- Build a small physical model to be tested in the hydraulics lab;
- Perform a cost/benefit analysis on the FPH design;

2. Background information

2.1. Flood data

Floods arise from a variety of causes and assume differing levels of severity. The most dangerous floods result from storm surges, when strong (hurricane-force) winds push ocean water up onto dry land. Likewise, riverine floods can have disastrous consequences if water is released due to a dam failure or the abrupt release of an ice jam. In both circumstances, the floodwater flows with tremendous power and arrives suddenly. Flash floods, though usually not as severe, occur with little warning when large amounts of rain fall in a brief period. Flash floods often catch the general population off guard, and are capable of sweeping away trees, cars and other large objects. The majority of floods are caused by heavy rainfall, which can continue for several days and cause rivers to overtop their banks. Indeed, most floods develop in this manner in Britain(2). Such floods are not as strong as flash floods, but their economic costs and social disruption can be enormous. The following table of total global damage reiterates the devastating impact of floods in the modern world.

Table 1 ***1997~2001 Global Floods(3)***

Year	Events	Known Dead	Number Displaced	Known Damage Estimate (US$)	Type
1997	96	4,369	2,294,500	8,678,100,000	Rainfall 100%;Storm 12.5%;Snowmelt3%
1998	165	24,230	43,274,701	234,933,680,000	Rainfall 100%;Storm 14.5%;Snowmelt 4.8%;Slides 2.4%
1999	102	34,016	18,327,718	24,065,851,000	Rainfall 100%;Storm 12.7%;Snowmelt 4.9%;Slides 15.7%
2000	102	10,724	50,224,361	13,354,700,000	Rainfall 100%;Storm 9.8%;Snowmelt 2%; Slides 9.8%
2001	135	4,346	10,445,059	8,997,095,000,000	Rainfall 100%;Storm 11.1%;Snowmelt 3.7%;Slides 16.3%

Many people believe that floods are becoming worse in the UK. Insurers paid out £242 million in domestic flood claims following the devastating autumn floods of 2000. The preceding year was already bad enough with £49 million in claims, and floods also dominated newspaper covers in 1998. Serious floods hit south eastern England again in 2001. However, the last floods on the same scale were back in 1947(4).

2.2. Example case: Yalding

A site visit to Yalding, a village in Kent that suffered from the 2000-2001 floods, enabled the design team to acquire some valuable information. Five of its communities were flooded repeatedly from early October to January. Yalding is situated at the junction of three rivers: the Medway, the Teise and the Beult. 16 people took advantage of the local council's temporary shelter, and many more evacuated to elsewhere. The inn where the design team stayed was inundated by approximately one metre of floodwater for two days. Surprisingly, most Yalding residents did not institute any real protection methods, either during or after the floods(5).

2.3. Mitigation techniques

Many techniques exist to mitigate floods' impact on new and existing houses. Retrofitting methods are changes to existing houses to protect them against flood damage. Depending on the applied retrofitting method, it can either reduce or avoid structural damage within the house. Retrofitting/mitigation methods can be divided into six different types(6),(7).

2.3.1. Elevation

Figure 1 Elevation(8)

The aim of elevation is to raise the lowest inhabitable area above the BFE*. Depending on the size of the house, the existing foundation structure, the magnitude of the expected hydraulic flood pressure and the raising level, this can basically be done by either extending the existing foundation or extending the exterior walls.

Elevating existing foundations (open foundations or continuous foundation walls) takes place by enlarging the foundation or providing a longer foundation structure up to the BFE. Elevation by extending the exterior walls upwards creates an extra floor, where, depending on the height of the new slab, the space below may be a crawlspace (>4 feet) or dirt and debris on the old slab (<4 feet)(8).

2.3.2. Wet flood-proofing

The aim of wet flood-proofing is to allow water to pass through the lower levels of the house in a controlled manner. In this case, the main inhabitable levels are situated above the BFE. Interior and exterior hydraulic pressures are the same when water is allowed through the sub-BFE parts of the house, which reduces damage to the structural foundation. Damage to contents and building systems only occurs in the highly unlikely event of a super-BFE flood. The parts of the house below the BFE should be resistant to water, meaning that electrical outlets, sewage pipes and domestic machines have to be situated at higher levels.

2.3.3. Relocation

The aim of relocation is moving a house to higher ground where the exposure to flooding is eliminated altogether. Relocation consists of jacking up the house and placing it on a wheeled vehicle to transport it to the desirable site. In most cases, the existing foundation structure is not transported, but is instead rebuilt at the new location. Although this retrofitting method is the most effective, it is only applicable where safe land and sufficient financial resources are available.

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* BFE = Base Flood Elevation: the water surface elevation of the 1% annual chance flood, also known as base flood or 100-year flood.

2.3.4. Dry flood-proofing

The aim of dry flood-proofing, in contrast with wet flood-proofing, is protecting the house against floods without allowing water to penetrate the house. The options available to watertight the house include enclosures, sealants, membranes and coatings. Windows and doors should be made especially watertight by shields or panel closures. One-way valves are applicable to prevent water entering the house. If the expected water level is higher than three feet, the exterior walls and foundation should be adjusted to resist the horizontal water pressure.

***Figure 2 Applied floodskirt*[9]**

A new dry flood-proofing system is the Floodskirt, comprising of a flexible skirt extending out of a glass fibre duct in the ground. In a crisis, the skirt can be attached onto hooks that keep it fastened to the wall. Zips prevent the passing of water at junctions. When the flood has passed, the skirt has to be rolled into the duct again(9).

2.3.5. Levees and floodwalls

The aim of levees and floodwalls is to prevent floodwater getting close to a property. The levees and floodwalls act as barriers, and are situated within a certain distance of the property. The barriers can be divided into two sorts: natural and unnatural materials. Levees are natural barriers made of clay, sand or sandy clay. The unnatural (floodwall) types are made of cement block bricks or poured concrete. Next to the barriers, a sump pump has to be installed to control the seepage or infiltration. All openings within the barrier should be equipped with a closure.

2.3.6. Demolition

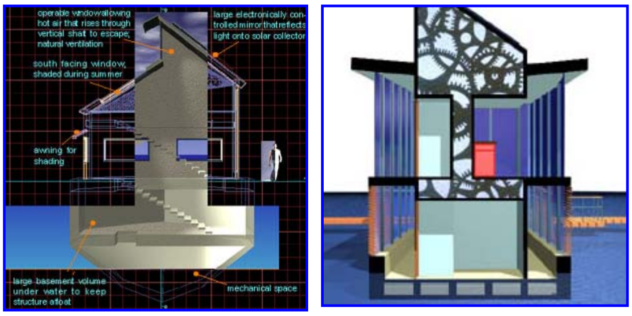
Demolition as a retrofitting method means tearing down a damaged house and re-building it on the same place or a less vulnerable spot. This method is only considered after a severe flood has attacked a house.

2.4. Emerging technologies

Protecting our houses and property from serious floods is a big challenge facing lots of researchers and companies all over the world. There are presently two main innovations to deal with it: floating houses and flood-shield houses.

2.4.1. Floating house

A floating house is a building that can float on the water due to the inherent buoyant forces in a flood. From an environmental view,



a. Cone-shape basement b. Raft basement

***Figure 3 Example floating houses*[10]**

it seems reasonable because it uses a natural energy force to solve the exact same naturally-occurring problem. These floating houses can generally be divided into two types according to their different modes of movement. One is the ‘boat’ floating house that can move freely in both vertical and horizontal directions. Another is the ‘lift’ floating house that can only move vertically up or down. These two types can both make use of a special basement or big platform to generate enough floating force to push themselves up. *Figure 3* shows two different floating houses(10).

The ‘boat’ floating houses sometimes use an anchor system to fix themselves in the same location and often employ a floating plate to connect single units together. The ‘lift’ floating houses use column support methods to guarantee the vertical movement of the houses: inside flexible columns and outside flexible columns. Some inside flexible column designs use only one centred control column as the axis of the house, leaving the house free to rotate around the column. Alternatively, in the outside flexible column design, there are several columns which are attached to the house by steel corbel or hollow telescoping tubing piers.

2.4.2. Flood-shield house

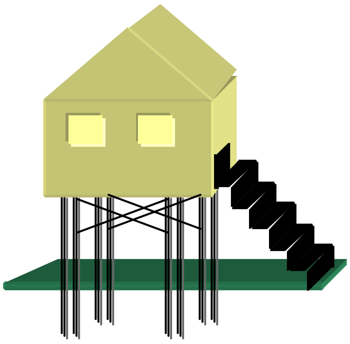
Besides pushing houses up to let floodwater flow through, researchers also consider covering an entire house with an exterior waterproof barrier to protect the property. Currently, two kinds of such barriers are in use. One employs a waterproof veneer, a facade with waterproof materials that is added to exterior walls and seals all openings, including doors. It is a reasonably inexpensive way to prevent flood damage, but high water pressure causes serious structural concerns to arise in areas where the flood depth may exceed one metre. The other method, already in use in Yalding, was discussed in the mitigation section of this report.

3. Preliminary options

Taking into account the mitigation techniques, emerging technology and our own brainstorming, some preliminary options for the FPH could be identified. Here, we also consider some advantages and disadvantages of each option.

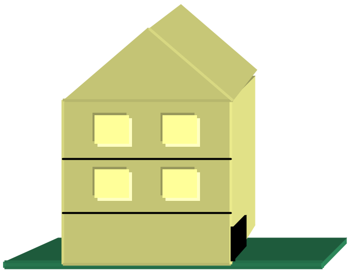
3.1. Elevation

Elevated stationary building structures are always strong candidates for newly built structures in flood-prone areas. These houses simply move the inhabitable level above the BFE. This can be done into several ways.



- *Building on extended non-movable columns*

The house is built on columns, where the slab is situated above the expected flood level. The house is accessible by stairs, which lead to the entrance of the building. The columns should be designed to resist the hydraulic pressure on the structure. Brackets can be used to stabilise the foundation structure.



- *Living areas above BFE*

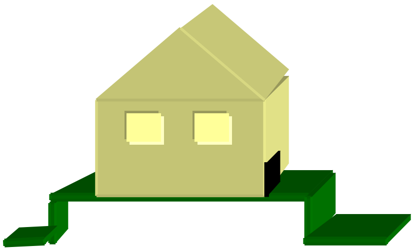
This house looks like a normal house, but inside the inhabitable areas begin on the first floor. The ground floor is reserved for storing supplies that have the least consequences if they suffer flood damage.

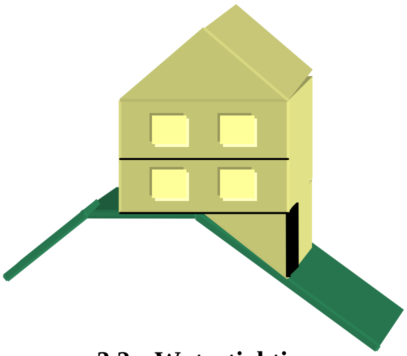
- *Building the house on a hill*

The house is built on top of a natural hill, which plateaus above the BFE. Close attention should be paid to the soil characteristics to avoid landslides when the soil becomes saturated during flooding periods.

- *Raising the level of the ground with fill*

This alternative uses a man-made hill. The soil concerns are the same as mentioned before, but the slopes can be adjusted according to a geotechnical engineer's recommendation.





- *Building on a decrease hill*

This alternative is a combination of building in habitable areas above the BFE and building on a hill. The direction of the flood should enter at the side of the garage, where the consequences of flood damage are minor.

3.2. Watertighting

The concept of a watertight house is to use special waterproof materials to cover the walls of the house along side particular methods to seal all of the building's openings. There are three parts of the house that warrant extra attention. Firstly, waterproofing the walls is no easy task. The outside walls require waterproof construction materials together with special waterproof paints or glues. At present, there are many kinds of concrete blocks used all over the world, including concrete composite blocks, empty concrete blocks and aircrete slabs that can be used in the watertight house if their surface is treated in advance. They are high quality, light weight and possess sound insulation. Furthermore, they are energy efficient and assemble quickly. Another advantage of such new materials is that they can be mass-produced in factories. Poured concrete can also be waterproof, given appropriate mixing and construction quality. The second area of attention is how to close the opening points of the house, especially the doors and windows. To prevent water entry without disturbing normal function, it is more appropriate to design an automatic rising and falling device, resembling a shutter, outside the exterior walls. For windows, a particular glass, similar to the variety found on submarines, can be installed outside normal window panes. Thirdly, a basement is a key element in the design because it might repeatedly become submerged in the groundwater.

3.3. Floating

The challenge of vertical-moving houses is enabling controlled movement in the vertical direction while maintaining lateral and rotational stability. The natural buoyancy of the water provides a potential lifting mechanism, but swiftly flowing water exerts strong horizontal force as well. Four design options were identified to satisfy this scenario: a column-and-sleeve system, a gas-filled basement, a below-grade raft and a series of anchors. These options are not mutually exclusive; a floating structure could include all four alternatives or any combination of them.

A column-and-sleeve system enables a house to rise during flood conditions, while leaving it in a normal grounded state at all other times. The system consists of a solid column that fits inside a slightly larger, hollow sleeve section. The fit needs to be snug, such that minimal lateral movement occurs as one section slides past the other. In addition, either rollers or viscous material must be present between the column and the sleeve in order to reduce friction. *Figure 4* represents our conception of a column-and-sleeve arrangement.

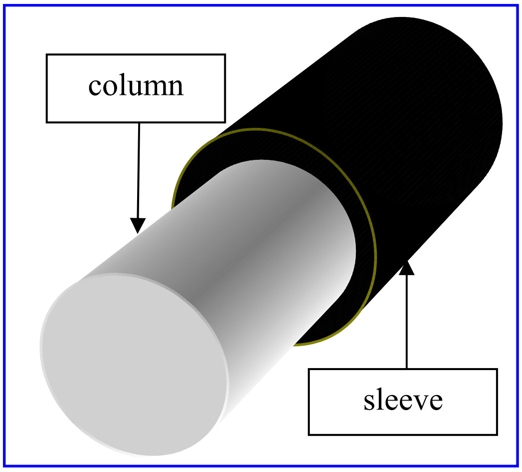


Figure 4 ***Column-and-sleeve system***

The column is fixed in position, embedded in a footing deep underground. The sleeve (and the rest of the house to which it is attached) slides up and down the column when sufficient vertical force is applied. The column may be inside or outside the house, but must be tall enough so that the house does not lift above the column, and thus become detached, during a flood. A house using this system would have a column-and-sleeve unit at each corner, at least. It may necessitate some internal members, too, depending on structural requirements. The idea, then, is that a critical depth of floodwater causes the house to float. The sleeves then guide the rising house in a purely vertical direction. The columns must be extremely sturdy in order to resist wind and flowing water's lateral force. They might also require enough flexibility to avoid fracture. During dry times, the columns may be helpful towards supporting the house's load. Structural concerns will determine whether such a dual role is feasible.

A gas-filled basement is a means to increase the structure's buoyancy. Due to its sheer weight, a house cannot float until the water level is well above its base. Therefore, the house itself must be watertight below that critical height. Watertighting methods are both costly and difficult to perfect. Wall stability poses another problem as external water pressure builds with increasing height. For these two reasons, minimising the critical floating height is beneficial. Using lightweight materials alone might not be adequate. The gas-filled basement works like a submarine, pumping a lighter-than-water substance into an empty chamber. That substance might be air, helium or another plentiful gas. Ideally, the basement could still be functional for storage or recreation.

A broad raft is another possible resource to help the house float. The raft could be made out of timber, concrete or a porous foam material. The broad raft has two main advantages over a regular basement: it provides rotational stability and completely eliminates the need to watertight the house's base. The top of the raft sits at ground level, and a grass covering can conceal it from public view. The raft's primary technical problem involves its anchoring mechanism. When the groundwater level rises above the bottom of the raft, but still below the ground surface, the raft must be restrained from floating. Thus, it requires a sophisticated anchoring system that can be released quickly in the event of a flood.

Lastly, like the column-and-sleeve arrangement, a series of anchors can prevent a floating house from drifting out of position. A house applying anchors is really more like a boat, though, in that the bottom must be rounded or barge-like for rotational stability. Also similar to the column-and-sleeve, the chains must be fixed to a solid footing deep underground. An anchored house inevitably has some horizontal movement. This design is relatively simple, but potential problems arise as the floodwaters recede. The house will have shifted from its initial resting place, so it must be realigned with its garden, driveway and other surroundings.

3.4. Analysis

At the end of the preliminary options analysis, a floating house was chosen with a watertight concrete basement and the column-and-sleeve units for lateral restraint. While elevated homes are perhaps the most economic and simple design, they are not without drawbacks. The stairs present a daily inconvenience, and many homeowners consider elevated houses to be aesthetically unpleasant. The bottom floor requires extra insulation on the lower surface, and erosion protection becomes necessary(11). In comparison to stationary watertight homes, floating homes avoid the hassle and cost associated with anchoring the ground slab and walls to resist hydraulic pressure. Also, floating results in a reduction in water height, and thus hydrostatic force. Most importantly, though, our group wanted to tackle a more unique and challenging project. The elevated housing market has little room for new ideas, but land-based floating homes have yet to become a reality. In order to seek a technically and economically reasonable system that only requires minimal input from the homeowner, the column-and-sleeve guided floating home is finally chosen as the design option.

4. Final design overview

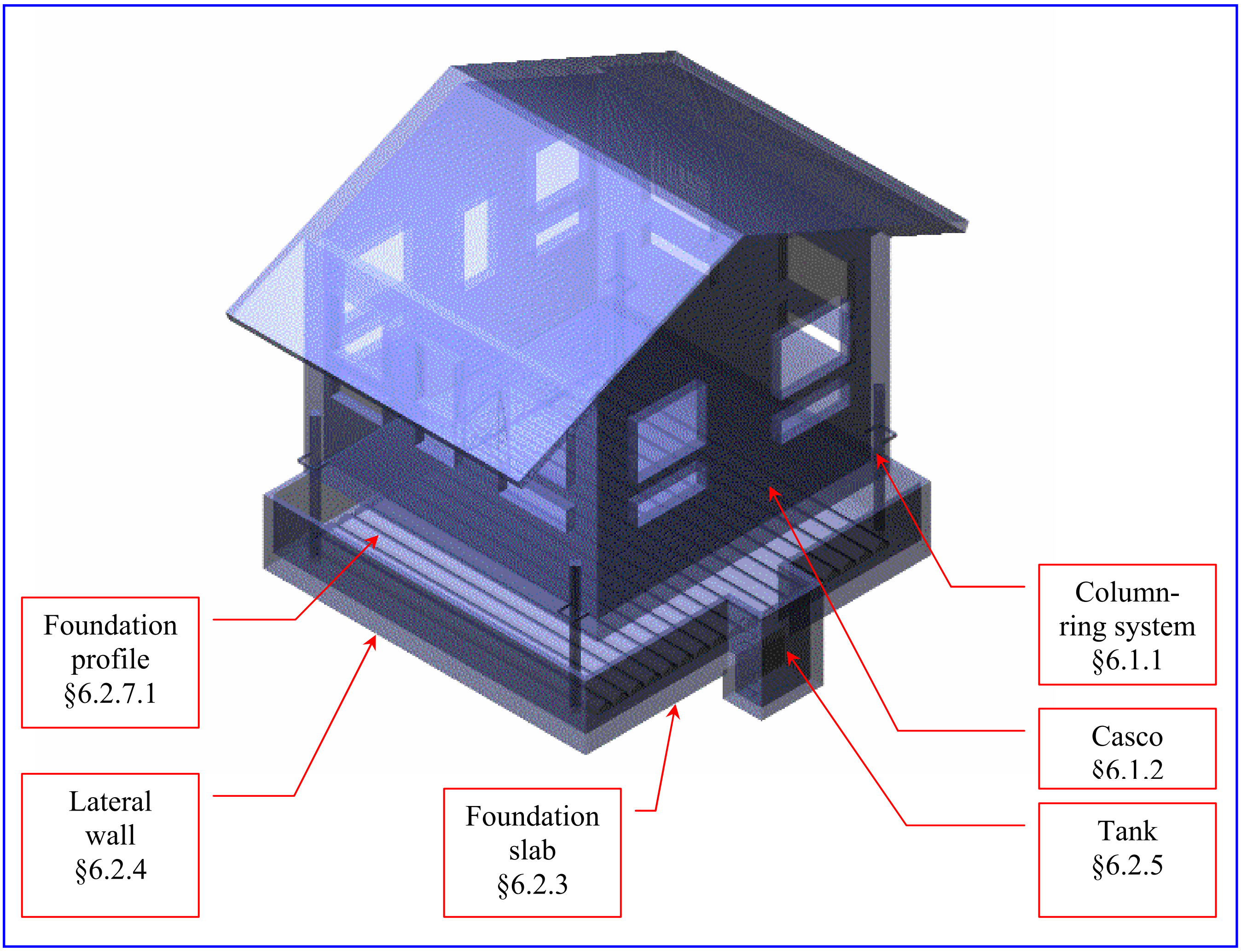


Figure 5 Final design overview

4.1. Summary

The final FPH design is a system of integrated components that enables the house to float with rising floodwaters and return to a stable position when the floodwaters recede. The above illustration identifies each of these major components. The house, itself, is a two-storey structure that sits partially (1.3m) below ground level. According to its weight, the house floats at an approximate water depth of 2.0m. This depth translates to a flood level 0.7m above the ground surface. Thus, in normal dry conditions the house rests stationary on its foundation. During a flood, the FPH begins to float as the water height surpasses 0.7m above ground level. The house continues to rise up to a maximum water height of 3m above the ground. Although our design satisfies the arbitrary maximum flood level of 3m, this value could easily be increased by extending the columns and revising some of the associated structural calculations. In other words, the FPH is a flexible design that can be modified to suit variable environments. The design's importance lies in the mechanisms, which can be grouped into two categories: the flotation system and the foundation system. Referring back to *Figure 5*, the casco and column-and-ring units comprise the flotation aids, while the foundation's components include the lateral walls, the foundation slab and the sedimentation scheme (bumps, tank and filters).

To begin with the casco, this reinforced concrete box makes up the bottom third of the house. The term "**casco**" is a Dutch word, roughly equivalent to caisson. This word was adopted following a trip to the Netherlands, which we explain further shortly. The casco is the only part of the house that comes into direct contact with floodwater, so it must be 100% watertight. Structurally, the remainder of the house above the casco is timber-framed on account of its light weight. The casco's interior is also the ground floor of the home, similar to any other residence.

As the house floats during a flood, the column-and-ring units provide lateral restraint to prevent the FPH drifting away. These external columns do not bear any vertical load; they just guide the house up and down. The rings, fitted with rollers to reduce friction on the columns, are attached to the casco via steel plates.

Moving on to the other components, the foundation provides the FPH with a permanent reinforced concrete base. Instead of having separate footings, the columns tie directly into the foundation slab. They require a large supporting mass to counter the overturning moment that the house exerts on the guide columns. The foundation consists of a slab and lateral wall. The wall prevents earth collapse while still allowing groundwater to enter the cavity through numerous holes. The "bumps" on the foundation slab are crucial to the sedimentation scheme.

The sedimentation scheme is necessary to deal with large sand/silt deposits that might otherwise destabilise the foundation following a flood. A filtration net between the casco's ledge and the top of the lateral wall should prevent most gravel-sized particles from entering the foundation. Nonetheless, silt, sand and random debris will inevitably find a way in. If permitted to accumulate on a flat base, these particles could leave the house in a permanently tilted position. Thus, the top of the foundation slab includes rounded contours to force sediments into trenches. After the flood has departed, a high-pressure water hose can be used to push these deposits into a collection tank. In turn, a pump then returns the silt-rich water to the surface.

All of these FPH components are discussed in more detail in the remainder of the report. Discussion is of a qualitative and quantitative nature, with calculations generally included in the Appendices.

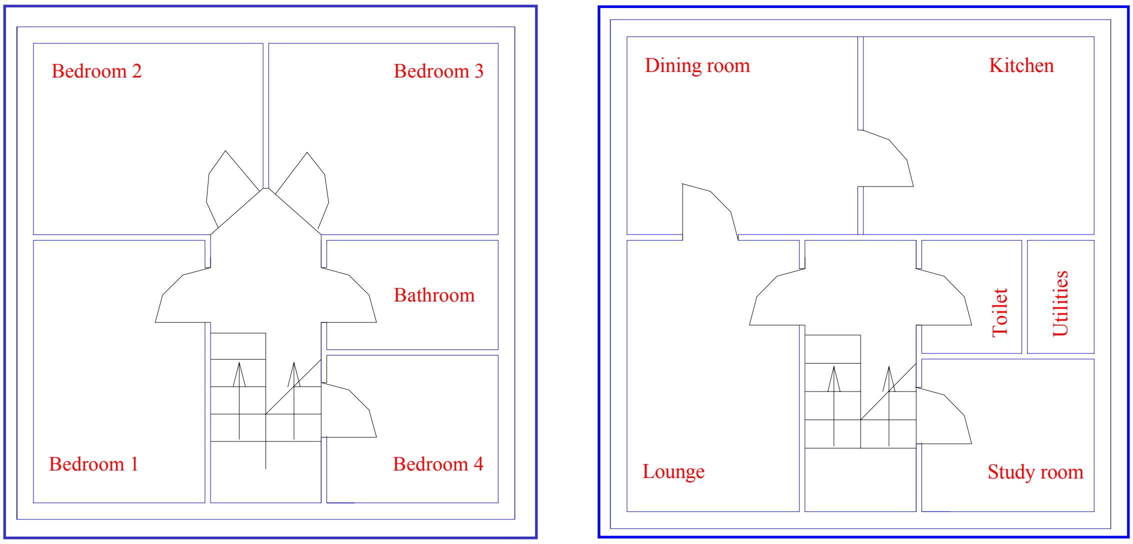
4.2. Example case: the Netherlands

As mentioned earlier, the design team visited the Netherlands to confirm the feasibility of our design prior to undertaking calculations. In the Netherlands, two sites were visited that host **permanently** floating homes. These structures did not have our foundation/sedimentation concerns, since they were always afloat. Regardless, the floating mechanism was largely the same, employing a concrete basement attached to external columns. The success of the Dutch homes also encouraged the team to make a notable design modification: reducing the column-and-sleeve to a column-and-ring arrangement. This simplification saves materials and eases the demand for accurate construction. With the prototype's viability bolstered by the Netherlands visit, the project then proceeded to the detailed architectural and structural design.

5. Architecture

5.1. Interior layout

The architecture layout of this Flood-Proof House is very similar to a normal house. This design is a 4-bedroom detached house with two storeys.



Groundfloor

First floor

Figure 6 ***Architecture plan***

In the plan (*Figure 6*), there are four bedrooms and one bathroom on the ground floor. A kitchen, dining room, study room, lounge and a toilet are arranged on the first floor. To reiterate the point, the house is able to host similar room sizes and arrangements to ordinary houses.

Two special features in our design are the position of the front door and ground floor windows, both shown in green in the architecture section drawing (*Figure 7*). Because the casco is waterproof

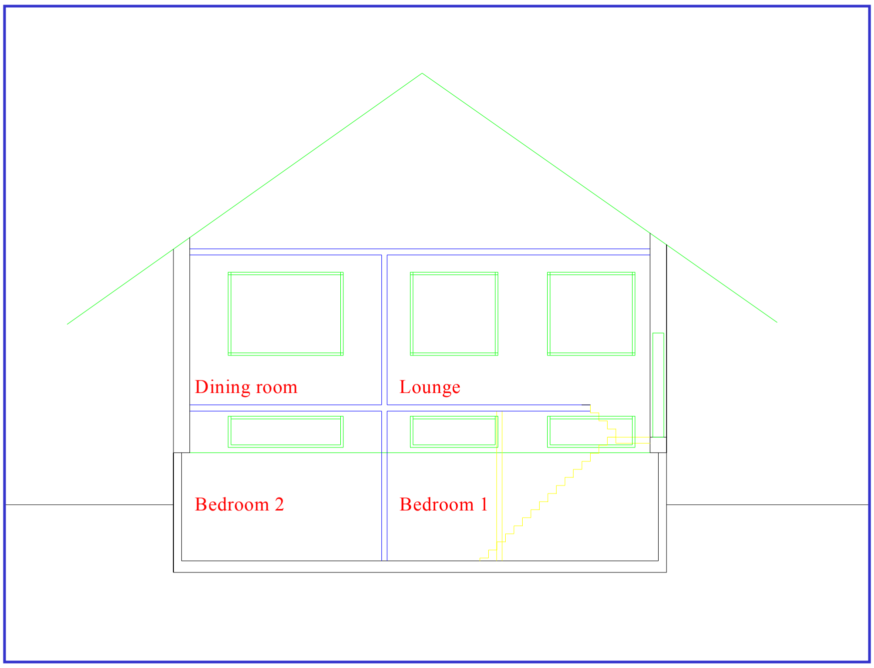


Figure 7 ***Architecture section***

and partly submerged during a flood, no holes could be made in it. Therefore, the front door is placed on top of the casco, which is between the ground floor and the first floor. Upon entering into a small foyer, people can take stairs to either floor. Likewise, the position of windows in the ground floor is high to avoid discontinuities in the casco. Plenty of sunlight can still enter through widened windows.

5.2. Utilities

Enabling constant usage of utilities, such as water and electrical power, during a flood without resorting to emergency sources requires a technique where the utility transport takes place in the 'dry' zone. Besides this concern, utility pipes should allow for vertical and lateral movement. Flexible pipes provide a simple solution for this latter requirement. Floating homes in the Netherlands already use flexible utility connections successfully. These flexible pipes can be made of rubber or plastic (polypropylene) materials, which are resilient and protective. The flexible pipes have to be located on one side of the house at least one foot above the Design Flood elevation(11). At this point, the utilities collect together and are transported though the flexible pipes to a box situated on top of one of the house's external columns. Once inside the stationary box, the utilities are transported down through the column towards the bottom, where they are connected to the existing utility services network underground. To be safe, all fuel lines exposed to flooding should be equipped with automatic shut-off valves in case the lines are broken.

This mode of transportation is difficult to apply to sewage as the sewage requires a powerful pump to prevent accumulation at the lowest point of the flexible pipes. Therefore, the sewage line is connected vertically under the house, separate from the other utilities. To prevent floodwater entering a facility through the sewer system and creating internal flooding, backflow prevention valves are installed on the building's sewer lines.

6. Structural design

6.1. Flotation system

6.1.1. Column-and-ring

The column-and-ring units provide horizontal stability while preventing lateral translation of the entire Flood-Proof House. The four columns are located at each corner of the house, within half a metre of the casco's outer wall face. The rings are not completely snug with the column; a nominal gap of 2cm exists. This gap serves two purposes: it allows intermittent friction-free vertical movement and permits a margin of error during construction. The gap is kept sufficiently small so that, if an irregular live load distribution causes an imbalance in the floating house, the tilt is limited to a few centimetres. The exact column and ring dimensions were determined independently.

6.1.1.1. Column

Each column is a steel, circular hollow section (CHS) designed for flexural strength (ultimate limit state) and deflection (serviceability limit state). Steel is a comfortable material choice because of its high stiffness (Young's modulus $E \approx 200\text{kN/mm}^2$), ready availability and resistance to corrosion in a marine environment (with an appropriate protective coating). The circular shape provides equal resistance regardless of wind and water direction. An assumption is made that the four columns equally share the horizontal load exerted by the house. The following horizontal forces push on the house:

1. Wind force = 80kN (worst case scenario from BS 6399: Part 2 – see Appendix A(12))
2. Pressure of water = 0kN (same on every house face, so zero net force)
3. Drag force of flowing water = 75.6kN (see Appendix B)

In addition, a small drag force operates on the column itself. Taking these forces in combination, Appendix B shows the calculations leading to the column dimensions. The maximum allowable deflection, 21mm, comes from BS 5950 for cantilever columns(13). In our case, defection turned out to be the limiting factor in order to guard against the rings jamming on their way up the columns. The final column dimensions are:

323.9mm diameter x 12.5mm thickness

This column size is a standard CHS from BS 4848 Part 4: Specification for Hot-Rolled Structural Steel Sections(14).

6.1.1.2. Ring system

Around each of the four columns a ring system is situated, which disables lateral movement as the house hovers in the floodwater. The ring system is situated at a position one metre above the bottom of the casco and thus, under normal circumstances, in the foundation profile and therefore not visible. The ring system actually consists of two connected rings: firstly, an outer ring that is attached to the house. Within this outer ring are four cylinders of steel, which are partly covered by plastic rollers. The plastic rollers are able to guide the process of vertical movement without causing much friction and damage to the ring system or the column.

Refer to Appendix C for the calculation of the outer ring, the steel cylinders and the connection of the rings to the house. All the calculations have been made according to BS5950. Summarised underneath are the sizes obtained:

Size of the outside ring:	**width 550 mm, length 550 mm, thickness 36 mm, height 100 mm**
Size of the cylinders:	**diameter 55 mm**
Connection to the house:	**4 bolts M12 each side**

An overview can be seen in ***Error! Reference source not found.*** and *Figure 9*.

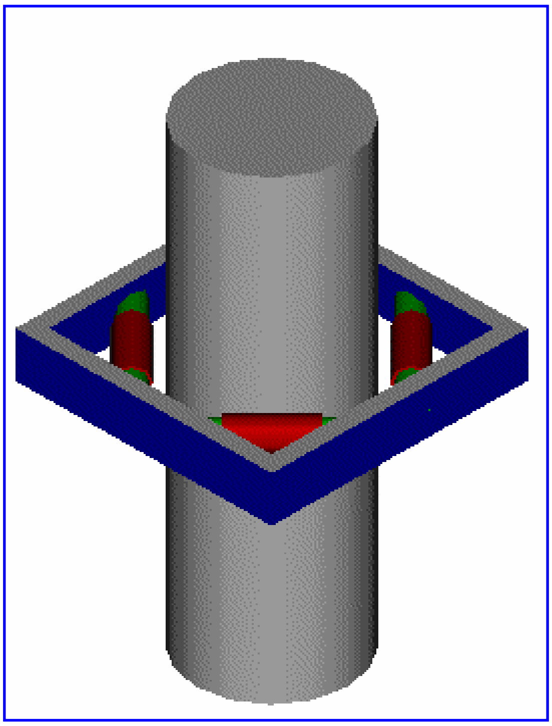


Figure 8 Top view of ring/column system

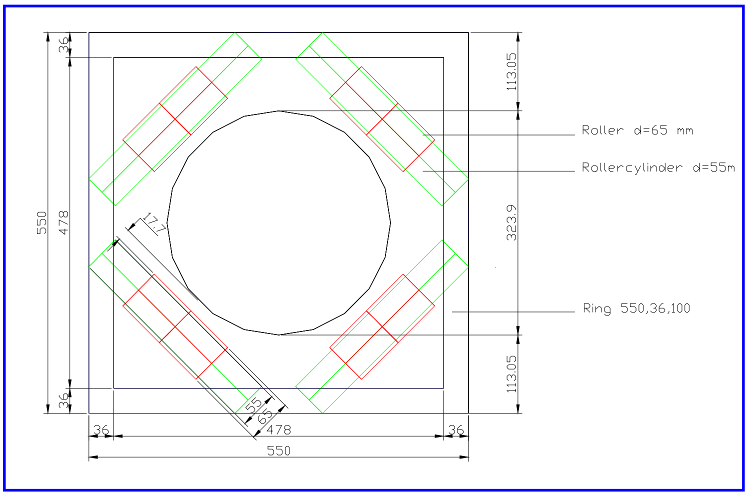


Figure 9 Overview of ring/column system

6.1.2. Casco

The casco, or reinforced concrete box serving as the FPH's raft, was designed according to British Standards 8110: Structural Use of Concrete and 8007: Design of Concrete Structures for Retaining Aqueous Liquids. Although the latter title refers to retaining liquids, it is equally applicable to the exclusion of water, as stated in the "Scope" clause. The casco's geometry coupled with the reinforcement layout according to these British Standards produces a completely watertight structure.

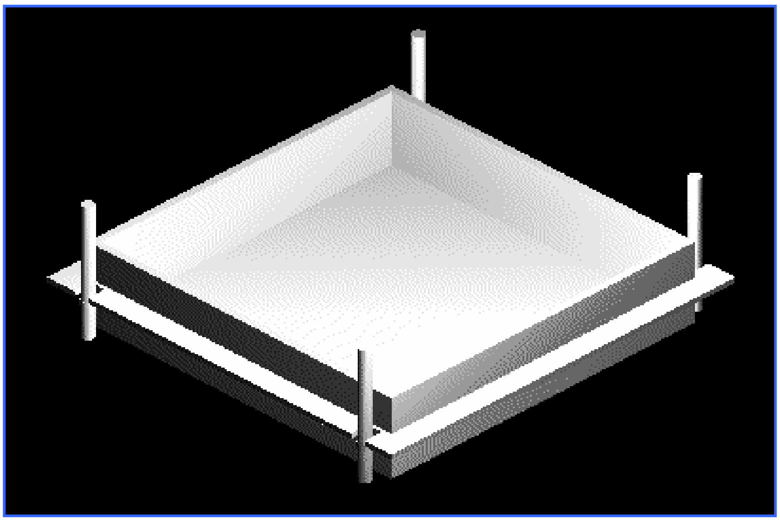


Figure 10 Casco with columns

Practicality dominates the casco's geometry. It is rectangular rather than rounded or another shape, in order to retain the appearance of a normal house. Furthermore, its simple shape facilitates the construction process, and accuracy during construction is vital to ensure full water resistance. It is 2.3m high, of which 1m is above the ground surface. Since the house floats as water reaches 0.7m above the surface, the top 0.3m of the casco remains above the water at all times. This safety zone makes allowance for small ripples/waves in the water and deviations in the house's interior live loads (e.g. extra furniture). The FPH's front door is on the top of the casco, which is also the concrete/timber frame interface. The horizontal ledge around the casco (pictured in *Figure 10* but omitted elsewhere) is flush with the ground when the house is in its permanent position. This ledge covers most of the gap between the casco and the foundation's lateral wall for both aesthetical and safety reasons.

The specific reinforced concrete design resists flexure, shear, compression and cracking. The entire casco can be a monolithic concrete pour to avoid possible leakage and weaknesses at joints. During the reinforcement analysis, however, the slab and walls can be assessed individually. Cracking applies to all elements. All of the pertinent casco calculations in the following discussions can be found in Appendix D.

6.1.2.1. Concrete properties

The concrete's properties deserve special attention in order to ensure a waterproof casco. The exact aggregate will depend on what is available near the construction site. However, our thermal cracking calculation assumes a conservative aggregate coefficient of thermal expansion of $12E10^{-6}/°C$(15). The next section on cracking discusses the effect of this coefficient. The casco is regularly exposed to groundwater, which equates to "severe" conditions according to Table 3.3 in BS 8110(16). Therefore, the concrete should adhere to the following minimum/maximum quantities:

Min nominal cover = 40mm
Min concrete grade = C40 (f_{cu} = 40N/mm^2)
Min OPC (cement) content = 325kg/m^3
Max water/PC ratio = 0.55

6.1.2.2. Cracking

Two major forms of cracking are prevalent: thermal cracking and flexural cracking. Thermal cracking is mostly dependent on the concrete's properties, particularly the cement content and the aggregate's coefficient of thermal expansion. Assuming an OPC content of 350kg/m^3, which is more conservative than the minimum value stated above, the corresponding T_1 value of 25°C could be made(17). T_1 is the temperature gradient between hydration peak and ambient. This gradient then yields a maximum crack width. Flexural cracking depends on the amount and position of reinforcement. The reinforcement affects strain values, which themselves translate into crack widths on concrete members' tension faces. Minimising crack width is obviously an essential factor when repelling water from a concrete structure. BS 8007 mandates that crack widths must not exceed 0.2mm for concrete in a "severe" environment. Thermal and flexural crack widths were checked (satisfactorily) following the slab and wall designs for flexure, shear, etc.

6.1.2.3. Casco slab

The casco slab is designed to satisfy flexure, shear and compression requirements, in addition to the cracking checks mentioned previously. The slab is a fairly unique concrete element, because it is cast monolithically with the walls and endures upward force (water buoyancy during a flood). In its normal position, the casco slab is continuously supported by the foundation's bumps. The spans are sufficiently short between each bump ($\approx$ 0.5m) to clearly see that this situation is not the most critical.

A much more severe moment arises when the house is floating due to the considerable buoyant force on the slab. This case demands a two-way slab design.

Therefore, the casco slab, subject to uniform upward loading, experiences negative (hogging) moment in the centre and positive (sagging) moment near the edges. Calculating these moments manually would be tricky. Fortunately, BS 8110 includes a table of moment coefficients to simplify the process. Applying these coefficients results in the considerable moments of -47.4kN-m at centre span and +63.2kN-m at the edges.

The moments obtained from two-way slab analysis must be modified to take axial compression of the slab into account. Water applies pressure to the casco's mostly submerged walls, which transfer compression to the slab. Thus, the slab can be considered as a series of adjacent 1m wide columns. Clause 3.8.3.1 of BS 8110 enables us to calculate an additional centre-span moment attributable to the columns' deflection. This new addition results in a total mid-span moment of -55.4kN-m, while the edge moment's change is negligible.

The reinforcement layout for the casco slab is depicted in Appendix J. In the centre of the slab, the top layer is tension reinforcement and the bottom layer satisfies minimum reinforcement requirements. At the edges, the bottom layer has the largest area of tension reinforcement. Here, though, the top layer is more than just the minimum percentage in order to provide adequate torsion resistance as outlined in BS 8110.

6.1.2.4. Casco walls

The casco's wall design is similar to that of the slab, dependent on slab flexure, shear, axial compression and cracking. Since all four walls are subject to identical forces, only one is needed for the design purposes. Three main design differences apply to the wall as compared to the slab. Firstly, to establish vertical reinforcement, the wall is considered as adjacent cantilever beams of unit width. This interpretation is conservative because the timber frame actually provides reasonable lateral restraint (shear) at the top of the concrete casco. Obviously, maintaining a conservative design is favourable to ensure that wide cracks do not form on the external wall face. The next design mode involves direct axial compression. Unlike the slab, in which compression forces only added magnitude to the flexural moment, load-bearing walls require a check for the axial force itself. In our case, the cantilever in bending turns out to be more critical for vertical reinforcement. Thirdly, the wall can be viewed as a one-way spanning slab in order to determine the horizontal reinforcement. As was the case with the two-way spanning casco slab, BS 8110 has a table to simplify the moment calculation. This time, though, the additional moment due to compression force is considered insignificant since it mostly transfers to the casco slab.

The wall reinforcement scheme is shown next to the slab in Appendix J. In the external reinforcement layer, the vertical reinforcement satisfies the cantilever/column criteria, while the crossing horizontal steel is merely minimum reinforcement. By contrast, in the internal layer the vertical reinforcement meets the minimum requirement. Meanwhile, the horizontal bars arise from one-way slab design. The junction between the walls and the slab needs continuous reinforcement. The rebar in each component would require a 180° hook to satisfy anchorage length requirements.

Instead, 90° bends are satisfactory so that the rebar passes from the wall into the slab and vice versa. This arrangement protects the delicate wall/slab interface from shear failure while still adhering to anchorage length standards. Other lap-lengths and bends can conform to standards.

6.1.3. Timber skeleton

The remainder of the house above the casco consists of timber for structural stability. Timber is not as common as concrete or masonry in the UK, but it is gaining popularity. Oak was the material of choice made famous during the Tudor period, but softwoods are now prevalent in residential timber frames(18). The FPH's timber frame can correspond to typical design standards, with load-bearing walls and interior partitions, beams to support floor panels and a trussed roof. The timber frame design should be straightforward since most of the ground floor consists of the solid, concrete casco. However, it is beyond the scope of this project to produce a detailed design of the timber frame, which would only be duplicating current patterns. The importance of the timber frame is its light weight, enabling the FPH to float in approximately 2m of water. Because the timber frame and other materials (tiles, windows, roofing, gypsum board, etc.) have not been specified, it was difficult to calculate the house's weight accurately. This calculation is not necessary, though, because we know that the 2m estimate is reasonable by other means. During the Netherlands visit, we saw two-storey homes, of similar area to our design, floating in only 1.5m of water. Furthermore, the casco's height can easily be adjusted following a comprehensive assessment of the overall house weight. A slight extension of the casco increases its floatability considerably, because the weight of displaced water is much greater than the added material weight. In other words, the exact depth of the casco below ground can be lengthened or shortened by a few centimetres to achieve the desired floating level.

6.1.4. Concrete/timber joints

The concrete/timber frame interface can be joined via adhesive and mechanical fasteners to retain complete water resistance and structural stability. Mechanical fasteners include simple nails, screws, toothed plates and indentations(19). In the case where it is necessary to achieve 100% effective bending stiffness between the two elements, steel lattices or steel plates glued to timber are appropriate choices. Another available option is to cement base studs into the top of the casco, providing easy attachment points for mechanical fasteners(18). More important, still, is the adhesive between the concrete and timber. BS 1204 specifies WBP type adhesive, water and boil proof glue capable of operating in severe exposure conditions. A brief calculation demonstrates that this adhesive can easily withstand anticipated shear forces in our design.

6.2. Foundation design

6.2.1. Structure brief

The foundation is one of most original parts distinguishing the FPH house from a normal house due to the special need to accommodate the columns, mobile casco and the sedimentation system. Five main elements form the foundation: the slab, lateral walls, column footings, bumps and the tank. *Figure 11* points out the main elements of the foundation. The whole structure generally looks like a concrete box, but having an additional part, the sediment collection tank. The foundation has four main purposes:

- To transfer the entire vertical load from the house to the ground
- To stabilise the column to help the house easily float up and down
- To provide a stable and flat surface supporting the house
- To resist lateral earth pressure

As discussed before, the purpose of the bumps and the tank is to solve the sediment problem, while the slab is primarily to stabilise columns and dissipate the vertical load of the house. The main horizontal forces on the columns are water's drag force and wind, which act indirectly via the house. This horizontal force is the principal consideration of the stability analysis for the entire house and the foundation, which is described in detail later. At the first design stage, the column footings were designed as an extra region below the 15cm thick reinforced concrete slab, shown in *Figure 11*. However, the structural analysis of the slab area directly connected to the footings is very complicated and dangerous shear conditions arise. Thus, a better solution is to remove the extended footings and consider them instead as one unit with the slab, using thicker concrete. The final calculation results show that the entire foundation is stable and the settlement is less than 1cm, depending on the soil hardness.

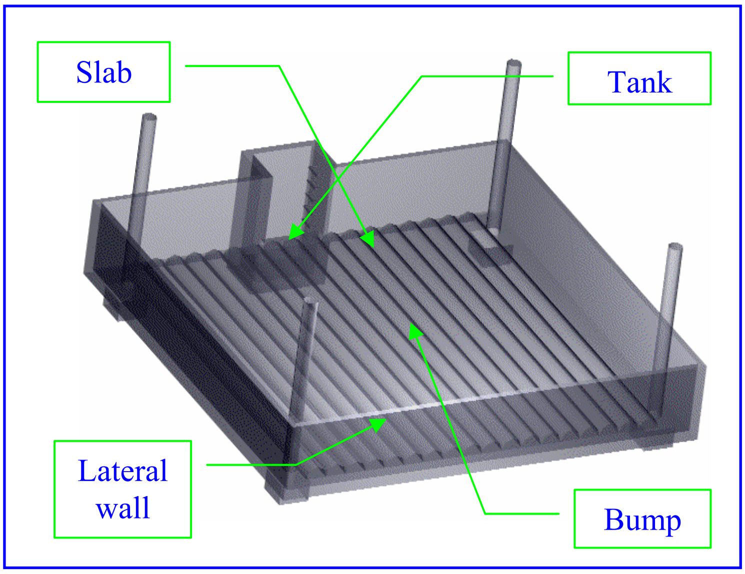


Figure 11 Foundation of the FPH house

The bottom of the tank is below the foundation slab in order to facilitate the flow of sediment-rich water into the tank during the post-flood cleanup. Thus, the lateral wall and slab at this section are different from the rest of the foundation. The thickness of the majority of the lateral wall is 15cm, while the wall thickness at the tank is 20cm to support the additional earth pressure (2.55m compared to 1.55m). Separate calculations for these two walls are provided in a later section.

6.2.2. *Stability analysis*

During a flood, horizontal forces create moments on each column, which might lead to rotation of the foundation. In the rotation calculation, the weight of the foundation is used to overcome the moment. Increasing the thickness of the slab is a practical method. The simple drawing below depicts this scenario. From the calculations in Appendix E, we choose a 410mm thick foundation slab. The thick slab also doubles as a footing for the steel columns. So, additional footings beneath the slab are not necessary.

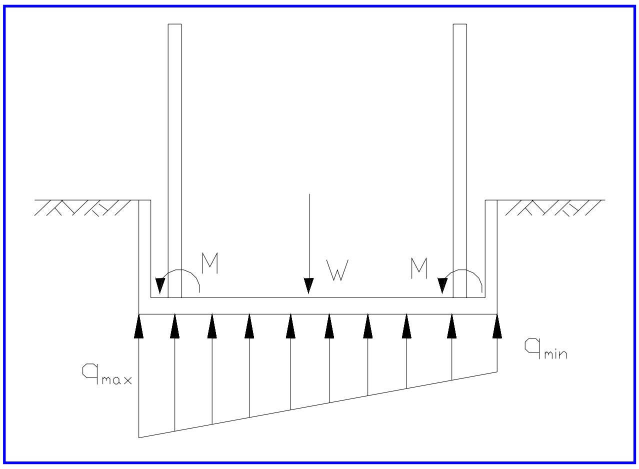


Figure 12 Rotation calculation

After satisfying rotational stability, a check must be made for settlement. Soil characteristics can vary widely in a floodplain, making it difficult to decide the soil type. So, two options are selected: one is medium dense sand, which is a good condition; and another is soft clay, which is a bad condition. For these two options, both vertical bearing capacity and settlement are checked.

a. Medium dense sand

The geotechnical characteristics of medium dense sand used in this calculation are: $\Phi = 34^{o}$, $\gamma = 17.6kN/m^3$ and $\gamma_{sat} = 20kN/m^3$(20). In the ultimate limit state, the vertical bearing capacity of sand is 138,751kN, which is much bigger than the design force of 3594kN. In the serviceability limit state, settlements at 30 years are:

Maximum	0.6mm
Average	0.5mm
Minimum	0.3mm

The settlements are small enough to ignore. In the short-term, the settlement is only 0.75mm.

b. Soft clay

The geotechnical characteristics of soft clay used in this calculation are: $C_u = 30kN/m^2$ and $\gamma = 18kN/m^3$(20). The thickness of the clay layer is assumed to be 7.96m, in which there is just 6m depth of clay beneath the foundation slab. It is assumed that there is a sand layer under the clay. The calculation of settlement is based on that assumption.

The ultimate bearing capacity of the clay is 27,350kN, which is still much bigger than the design force of 3594kN. The net immediate settlement is 3.2mm, which is based on a plasticity index of 45 and an overconsolidation ratio of 3. The consolidation settlement is 4mm. These settlements are small enough to ignore(21).

To conclude, a 410mm slab for the foundation is to be used. This thickness has proven to be practical and reasonable in the calculations. The slab works as both the foundation base and a footing for the columns. The settlements in both medium dense sand and soft clay are acceptably small. The detailed calculations are shown in Appendices E and F. The reasons for giving up the extended footing design option are as follows:

- The interactions between each footing and the slab are very complicated and the calculation is unreliable.
- Eliminating extra footings makes the construction easier.
- The calculation of bearing capacity and settlement becomes simpler. Meanwhile, the possibility of error is reduced.

6.2.3. Foundation slab

As mentioned before, the thickness of the slab is 0.41m. The net size of the slab is 10.1m x 10.5m, from outer face to outer face. The moment transferred from the lateral wall is 18.01kN/m^2 at the ends of the slab.

In the stability analysis, the critical situation occurs when the foundation is still full of water while the groundwater level outside the foundation has dropped below the slab. Thus, the design load on the slab should include following forces:

- The weight of the house
- The self-weight of the foundation including the lateral walls, the columns, the slab and the bumps
- The weight of water filling the space between the house and the foundation

From these design loads, the resistance force of the soil can be calculated. The critical moment is in the section containing the steel columns because of the moment caused by the horizontal force on the columns. By contrast, the critical shear force arises in the section along the outside face of the house, 0.75m from the outside face of the slab. Thus, the steel bar arrangement can be determined according to these critical moment and shear values.

6.2.4. Lateral walls

The majority of the lateral walls' length is 1.55m high, although the 2.55m high tank wall is designed separately. The main design process follows five steps:

- Design loading analysis
- Assume the thickness of the wall
- Calculate the horizontal earth pressure on the wall
- Determining steel reinforcement to accommodate the ultimate loads
- Check the shear force and bond stress

When analysing the design loading on the wall, it is assumed that a medium sized car on the ground surface nearby imposes a load on the wall, but the construction imposed loads are not considered. Thus, the wall should be supported during the construction stage if there are significant extra loads on the ground near the wall.

Holes are incorporated close to the base of the wall to let groundwater in and out and relieve some of the hydrostatic pressure. Nonetheless, from intuition and tests run in the hydraulics lab, it is clear that water inside the foundation rises more slowly than groundwater on the outside. This different rate depends on the rising speed of the floodwater and soil conditions. Furthermore, there is a risk that the holes may become blocked by sediments and debris. Thus, the critical situation for the 1.55m wall is when the outside water level is at the ground surface (top of wall) while the inside water is ignored.

Given these assumptions, the resulting main steel bars in the 1.55m wall are 16mm bars at 250mm centres, while the secondary bars are 10mm bars at 250mm centres mainly for crack protection. In the 2.55m wall, 20mm bars at 200mm centres are used, and 10mm bars at 200mm centres are provided as the second layer. For crack control on the outer surface, horizontal 10mm bars at 300mm centres are adequate. Appendix G includes these calculations, while Appendix J summarizes the reinforcement.

6.2.5. The tank

The tank is designed to collect all of the sediment that remains in the bumps' trenches after a flood. Determining the volume of the tank stems from the anticipated amount of sediment discharge. From simple geometry, the volume of space between the bumps and the house is about 4.3m^3. Although our sedimentation calculations predict a much smaller figure, it could be assumed that the system reaches its maximum sediment capacity of 4.3m^3. However, to build a 4.3m^3 tank is impractical and uneconomical. Therefore, the sediment removal is divided into four stages, each stage needing the maximum volume of the tank to be 1.1m^3. To review the cleaning procedure, a jet of water is issued from the far end of the foundation to force the sediment along the trenches. The sediments and the water funnel into the tank, where a pump removes both. The size of the tank is conservative to allow for the fact that much of the sediment might settle before it can be pumped out. Finally, the volume of the tank is set at 1.5m^3. On one side of the tank's lateral wall, some steel ladder rungs are provided to help people climb in and out of the tank for maintenance and extra cleaning.

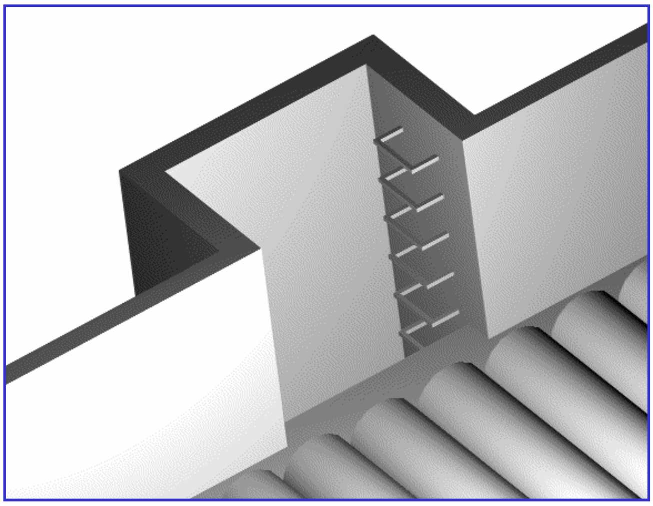


Figure 13 Tank close-up

6.2.6. Filtration system

As mentioned previously, holes are situated at the bottom of the lateral walls that enable water to enter and exit the foundation. To avoid large particles passing into these holes and either clogging them or entering into the foundation, a filtration system is considered. This filtration system consists of a vertical layer of sand (clean sand, $k = 1E10^{-4}$m/s), with a width of one metre in front of the four sides of the retaining wall. In addition, a geotextile can be applied to cover part of the retaining walls' surface, wrapping it up to a height of one metre. Allowing water to pass the geotextile while denying entry to particles requires that $k_{geotextile} > k_{soil}$. A geotextile of Typar 3807-4 Nonwoven Polypopylene can be used ($k = 1.6E10^{-4}$m/s)(22).

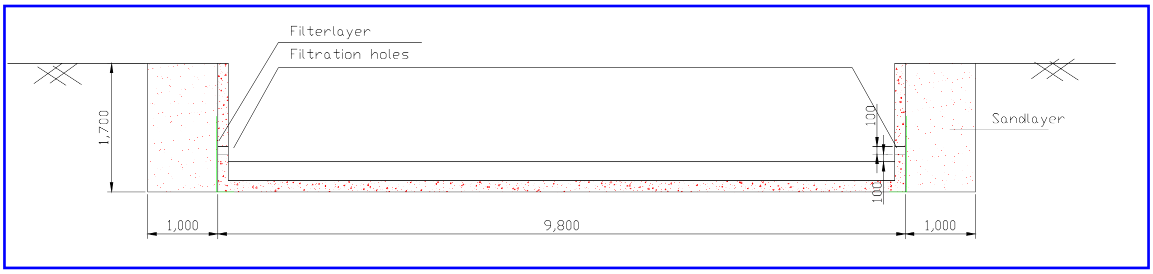


Figure 14 Overview filtration system

The structural calculation of the retaining walls presumes the worst case scenario, where the foundation is dry and the external soil is saturated. Since the reduction of hydrostatic pressure and wall strength due to the holes is ignored for this calculation, the primary function of water transportation determines the holes' size. However, most of the water transportation takes place towards the tank during the sediment cleanup process. Therefore, a refined calculation of the holes' size is not necessary, and assumptions are sufficient on this aspect. The radius of each hole is chosen to be 5cm, with five holes in each wall face positioned a distance of 10cm from the top of the foundation profile.

6.2.7. Sedimentation scheme

Ensuring stability of the Flood-Proof House under every circumstance requires a closer look at sediment transportation and accommodation during and after a flood. Sediment enters the foundation through holes in the retaining walls as well as overtopping them. The bumps in combination with the tank can take care of smaller sediments, like sand and silt. Larger debris might pose a more severe problem. Two basic systems are available to stop big particles entering the foundation. Firstly, a tough, fibre net can be attached between the casco and the foundation's lateral walls. As the flood rises and the house starts floating, the net pulls out of its roller automatically. Likewise, it retracts back into its roller as the house descends. This net is similar to a porous version of Floodskirt, mentioned in the Mitigation Techniques section of this report (see §2.3.4). Secondly, a filtration system covering the holes in the retaining walls is applicable (§6.2.6).

6.2.7.1. Foundation profiles

For the bumps to accommodate sediment brought by a flood, three profile options are considered. The purpose of these profiles is to keep the tops of each bump, i.e. the parts in direct contact with the casco, free of sediment. The basic idea for the foundation profiles is to create a space between these contact surfaces and the foundation slab to accommodate sediment. Besides this duty, they also enable better transportation of the sediment towards the tank after a flood. A foundation profile's success at forcing sediment into its trenches depends mostly on its shape. For the model, three foundation profile options are considered:

Option 1: a bump foundation profile, where the bumps consist of half circles with a radius of 250mm. The profile covers an area of 9m x 9.5m (*Figure 15*).

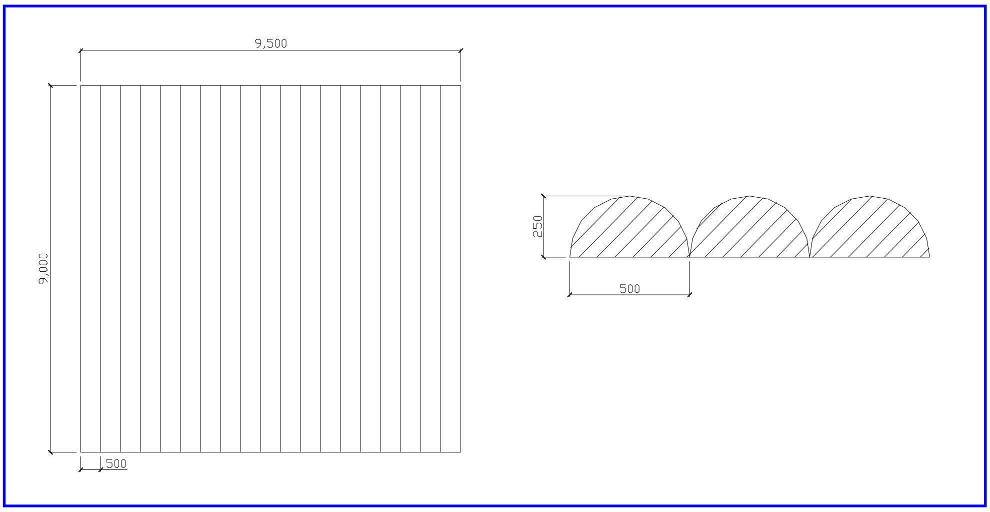


Figure 15 Option 1: Bump Profile

Option 2: a wave profile consisting of rounded peaks and troughs. The semi-circles have a radius of 150mm and the profile covers an area of 9m x 9.3m (

Figure 16).

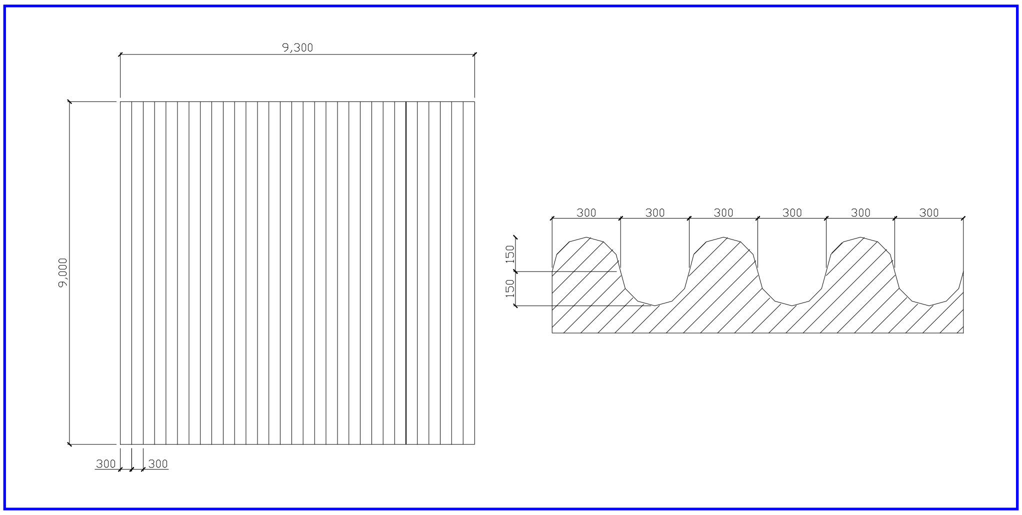


Figure 16 Option 2: Wave profile

Option 3: a flat-tooth profile, where each contact surface is 200mm and flat, to aid construction. The foundation profile covers an area of 9m x 9m (

Figure 17).

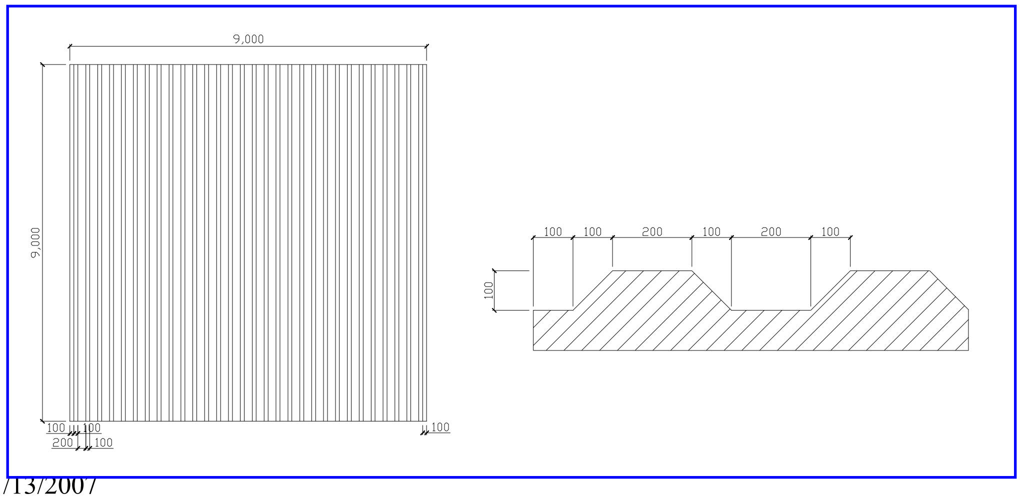


Figure 17 Option 3: Tooth profile

6.2.7.2. Determining the expected amount of sediment

For calculating the expected amount of sediment left in the foundation by a flood, the majority of particles are assumed to be sand-like (d = 2mm and $\rho_s = 2650$ kg/m^3). This assumption is reasonably valid because smaller, lighter particles can float over the foundation without falling and the filtration system obstructs larger particles. The suspended sediment concentration is assumed to be 500mg/l(23). Given our maximum flood level designation of 3m above the ground, the distance between the bottom of the house and the ground surface is 1m (3m - 2m floating depth of the house). Appendix H shows the calculation of the expected sediment discharge with constant flow. This constant flow calculation is very conservative; it does not take certain factors into account that definitely reduce the expected amount of sediment. The omitted factors are:

- The net and the filtration system helping to prevent a certain amount of sand entering the foundation.
- A flow of water entering the foundation also transports a certain amount of sediment away from the foundation.
- The water level in a flood rises gradually, and the horizontal flow is usually rather minimal (velocity ≈ 0m/s).

Appendix H also contains a calculation of the expected amount of sediment in the case of a gradually rising flood. It seems that taking into account the last assumption, less sedimentation will occur. All the calculations have been made for one profile alternative, as all the alternatives have a comparable ability to accommodate sediment.

6.2.7.3. Transportation of sediment by foundation profiles

To accommodate the tank size suggested earlier (see §6.2.5), washing the sediment into the tank probably requires four phases. At the end of the foundation profile, two slopes in the foundation slab lead towards the centrally-located tank. The slopes feed the sediment-filled water into the tank, where a pump removes it all in preparation for the next phase. *Figure 18* clarifies the sediment transportation process.

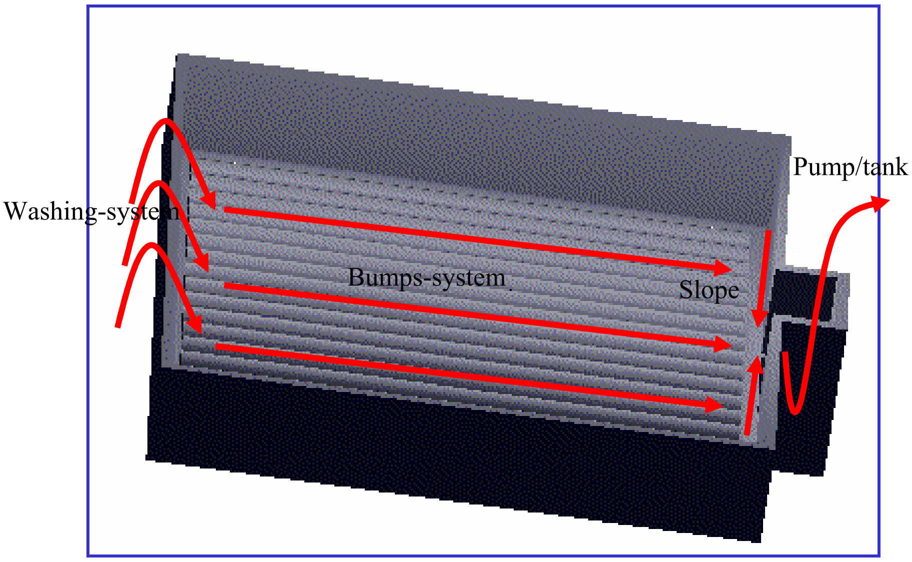


Figure 18 Transportation system

6.2.8. Model

A model of the Flood-Proof House has been built and tested in the hydraulics laboratory to observe the column-and-ring system in action and the accommodation/transportation of sediment along the three foundation profiles (§6.2.7.1). The model consists of the foundation and the casco, where the correct floating height of the house can be obtained by putting weights in the casco. Timber is the primary material comprising the casco and the foundation, while the columns and rings are metallic. Although these materials differ from the actual design, they are adequate for our qualitative observations.

6.2.8.1. Test

The model was tested in a controlled flume that enabled us to alter flow velocity and height. The model fulfilled the three scaling laws of similarity:

1. Geometrical similarity (scale 1:20, i.e. $\lambda = 20$)
2. Kinematic similarity
3. Dynamic similarity (to the extent possible)

Due to the limit of the flume capacity, a maximum flow velocity of 0.1m/s was used during the model testing, which is equivalent to actual flow velocity of $v_p = v_m \sqrt{\lambda} = 0.1\sqrt{20} = 0.45 m/s$. Measuring the flow area (depth = 17.4cm, width = 75.3cm) results in a discharge of: 0.1 x 0.174 x 0.753 = 0.01376m/s ⇒ 13.76 l/s

Multiplying the latter by the sediment concentration (500 mg/l) gives the mass of sediment per unit time: 0.5g/l x 13.76 l/s = 6.88g/s ⇒ 412.8g/min.

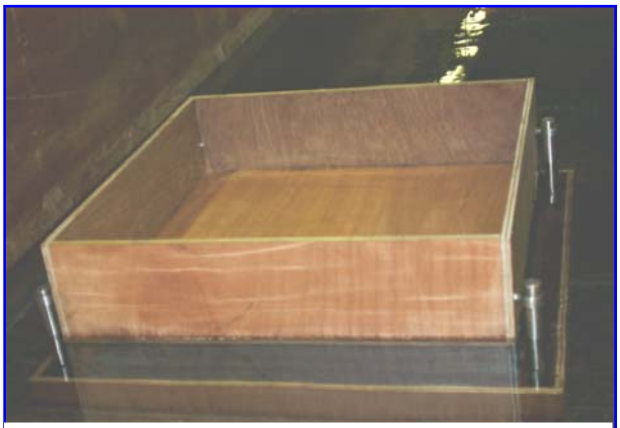


Figure 19 Model of the Flood-Proof House

For the sediment, some special lightweight plastic particles are adopted, which have been used successfully in many practical sediment transport tests in the past. These particles have an approximate fall velocity of 1cm/s. Although these mock sediments do not completely fulfil the laws of similarity, they come reasonably close to doing so.

6.2.8.2. Results

With water flowing at 0.1m/s, the model's casco had no problem moving vertically along the columns. The appropriate amount of sediment was mixed into the water prior to reaching the model, and it could be seen that most of the sediment falling into the foundation accrued at the rear part of it. In some cases, a small amount of sediment remained on the peaks of the foundation profile, mostly for the third foundation profile (the flat-tooth profile). This result was expected for the flat-tooth profile, and its ease of construction is likely overshadowed by unacceptable sediment accumulation. In general, the rounded profiles (bump and wave) fared well, with sediment collecting in the trenches until capacity was reached. It could also be seen that heavier sediment was situated at the front part of the foundation profile, while lighter sediment collected further down the foundation.

The complications in sediment interaction with structure and limitation of the scale model render the experiment result inconclusive. Although the foundation profile option two, the wave profile, performed the best, the endorsement of this profile is still premature. For example, the wave profile in the scale model consisted of a plastic material; the actual concrete foundation has a much higher coefficient of friction. Furthermore, sediment concentration and water velocity in real life are all random variables. The position of other houses and topography in the vicinity of the FPH also affects sediment interaction. Further testing in a broader environment under different scenarios is ultimately necessary. Still, from our observations, the wave profile seems to be a viable option as long as the sediment volume remains below capacity.

7. Construction

7.1. Construction sequence

The distinctive components of the FPH warrant careful consideration in regards to construction. For instance, the large amount of concrete required by both the foundation and the casco makes material availability and curing schedules critical. In this section, the major construction stages are explained, and some varying construction options are considered depending on the number of houses that need to be built on a site.

The following figure shows the side and front views of the FPH. The red part includes the foundation and the columns; the blue part represents the casco; the black part represents the rest of the house (mostly timber, with generic roof shown).

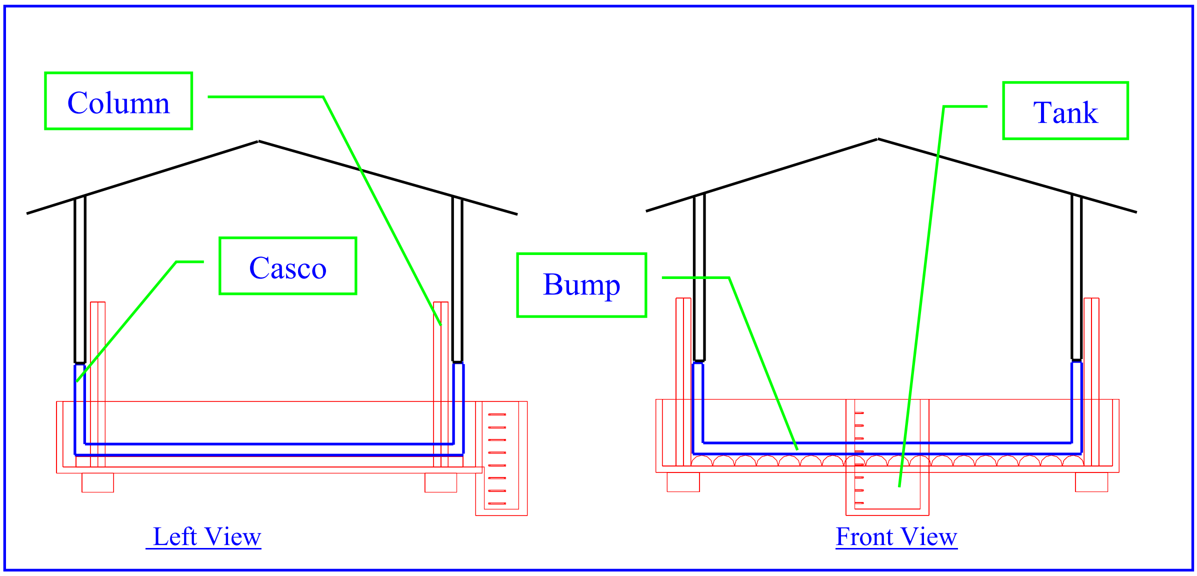


Figure 20 Side view and front view of the FPH

The construction sequence consists of eight main stages:

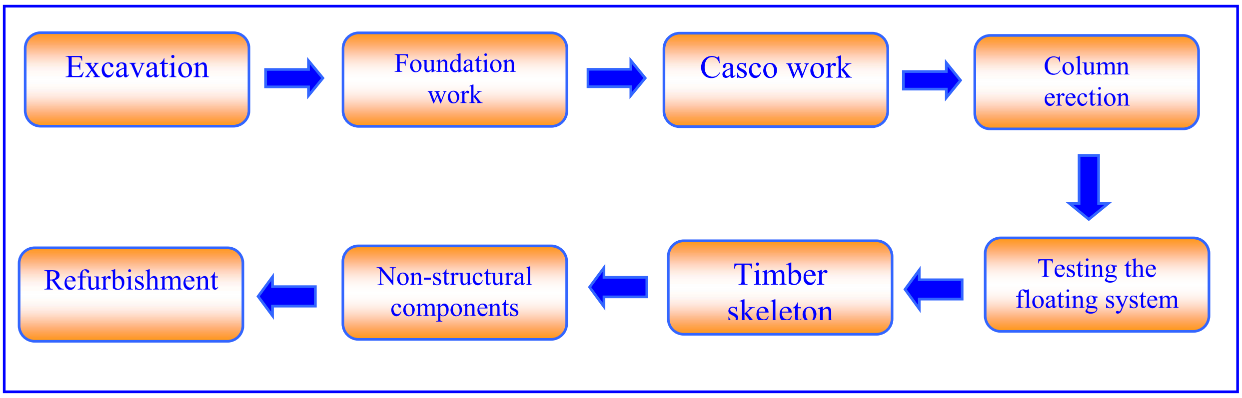


Figure 21 Construction phases

7.2. Excavation

The FPH calls for a considerable excavation volume, over one metre deep for an area of approximately 100m^2, plus the tank. Depending on the soil conditions, temporary slope protection measures are probably required during the excavation. High groundwater levels could further destabilize excavated slopes and necessitate pumping. Most importantly, the base soil must be compacted in order to prevent differential foundation settlement.

7.3. Foundation work

Foundation work includes the construction of lateral walls, the slab, the tank and bumps (the foundation profile). The first three elements pose little problem, they just require a lot of concrete and reinforcement. However, the bump profile is difficult to build on site due to its special arc pattern. Instead, the foundation profile should be prefabricated and assembled on site. The complete profile is about 9m long and 9m wide. To ease assembly on site, the profile can be divided into nine sections along the longitudinal axis (following the trench lines). Dowel bar splicers and special adhesive may be used to facilitate the tie-in of individual precast parts. To fix the bumps onto the foundation slab, some holding down bolts and steel plates are required along the ends of the profile slab. *Figure 22* illustrates this connection technique. All bolts and steel plates should have anti-rust treatment to avoid harm from groundwater.

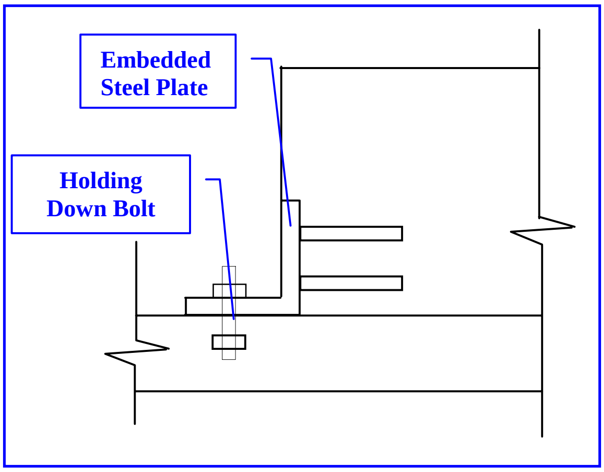


Figure 22 Slab/bump plateau junction

7.3.1. Casco work

The casco is perhaps the principal concern during construction, because significant construction flaws could result in unacceptable leakage. Two options exist: assembly from precast units and a monolithic concrete pour on site. Both options have their advantages and disadvantages, but money is probably the deciding factor.

Using precast sections divides the casco into manageable sizes, but requires assembly expertise. At 9m by 9m, the casco's bulk is a severe burden. A manufacturer can split this mass into four or five units, each approximately 9m by 2m. These units can be transported by lorries and floated along a river, assuming the floodplain lies near a river. A manufacturer can also guarantee high concrete quality, but skilled workers are still needed on site to assemble the units. Still, applying watertight adhesive and post-tensioned rods to the units should produce a waterproof structure. This method is probably uneconomical when building only several Flood-Proof Houses. However, for a whole community this approach likely saves construction time and cost.

Option two, pouring the concrete on site, requires a competent concrete contractor. The contractor has to coordinate the considerable reinforcement layout, correct ring position and formwork for a monolithic pour. The steel rings are bolted to steel plates embedded in the casco. Getting their position precise is crucial to the FPH's success, since they must align with the foundation slab's steel plates and the gaps in the casco's ledge. Formwork can be placed directly on top of the foundation profile for an in situ pour; later, the formwork underneath the cured casco can be removed during the floating test. Alternatively, the casco can be poured on adjacent ground and lifted onto the foundation by a crane. This method provides a better environment to lay formwork, but it necessitates a heavy duty crane. However, the precast option also mandates a heavy duty crane. The on-site pour might add construction time, but it also provides a viable option.

7.3.2. Column erection

Each guide column is fixed onto the foundation slab via embedded steel plates, which are coated with a protective layer. Accurate positioning of the columns, to within several millimetres, is essential. Establishing this correct position is largely dependent upon the ring location (already present), therefore reiterating the need to line the rings up properly. Excessive deviation in column position might cause the rings to jam on their way up the columns, disabling the whole floating mechanism.

7.3.3. Testing the floating system

Once the casco has cured, testing is an important step to check that the FPH is fully functional. Not only does a test confirm proper alignment of the column-and-ring system, it also ensures that the casco is watertight. If minor leaks are identified, they can be corrected using a number of treatments (chemical sealants, patches, etc.) before continuing with the construction process. The test method is simply filling the foundation with water and plugging the holes in the lateral wall. The empty casco floats when the water level rises to approximately 1.2m. The depth of the foundation is 1.55m, meaning floating can be observed for about a third of a metre.

The remainder of the construction process follows regular procedure.

8. Cost analysis

Due to the extra expense of the flotation system, the FPH's cost is higher than a normal house of comparable size. The following table gives cost estimates:

Table 2 Cost Analysis

Item	Quantity	Cost (£)		
		Materials	Construction	Total
Foundation				
Reinforced concrete[1]	$45.25m^3$	9050	1810	10860
Excavation[2]	$120m^3$	0	228	228
Other elements[5] (filtration)		500	200	700
Casco[4]				
Reinforced concret[1]	$35.4m^3/2$	3540	1416	4956
Other elements[5] (net, joints)		500	200	700
Column-and-ring system				
Steel columns and rings[3]		1460	500	1960
Flexible utility pipes				
Pipes[5]		500	100	600
Testing			1000	100
Total extra cost (£)				20494

Notes:

1. Total concrete of foundation = Slab + Lateral walls + Tank + Bumps

$$= 18 + 9.35 + 1.9 + 16 = 45.25m^3$$

The reinforced concrete's material cost is based on a unit cost of £200/m^3. The construction cost for the foundation is assumed to be 20% of the material cost, while the construction cost for the casco is assumed to be 40% of the material cost due to anticipated crane and formwork difficulties.

2. The total volume of excavation is estimated to be 220m^3, in comparison with a normal house's excavation volume (around 100m^3). Hence, the additional excavation volume stands at 120m^3. The cost of excavation is based on a unit cost of £1.9/m^3 from the CESMM3 Price Database(24).
3. The columns' cost is based on a unit cost of £1000/ton of steel. The total mass of the columns and rings combined is 1460kg, which equates to a material cost of £1460. This number plus a £500 erection cost is £1960.
4. Estimating the casco's additional cost is difficult, because a regular house also incurs costs on its ground floor. Assuming that the solid concrete casco is replacing mortar and brick construction, 50% of the casco's cost is estimated as surplus.
5. These numbers are based on similar projects and advisers from the industry.

According to a research report produced by the Corus Construction Centre(25), the average building costs (purely costs, not sale price) about £600 to £700/m^2. For a house identical to our FPH in size, this value translates to a total cost of £112,000. Thus, the FPH's estimated additional expense of £20,500 makes it 18% higher than a normal house. However, our estimates are based on one house. The cost gap narrows if multiple Flood-Proof Houses are built in one area simultaneously, on account of bulk concrete production, crane sharing, etc. Also, land prices in a floodplain are likely to be significantly less than elsewhere. Furthermore, reductions in flood insurance premiums should partially offset the added cost. Indeed, many insurance companies in the UK are threatening to withdraw all coverage for traditional homes situated in flood-prone regions(26). Although only a rough cost estimate is performed, it is clear that the FPH, while more expensive than traditional houses, is a reasonable investment. The financial analysis of this new type of house is optimistic.

9. Environmental assessment

The purpose of this design is to reduce flood damage for residents. Due to this special aim, this design automatically has a close relationship with environment. Therefore, an environment assessment is necessary. The impacts can be considered from physical and socio-economic perspectives(27).

9.1. Physical environmental impacts

This design has the negative impacts associated with any housing development (land usage, waste production, etc.), but additional disturbances should be minimal. Exploring a wide range of environmentally friendly measures is beyond the scope of this report, but some brief consideration has led us to incorporate a few green characteristics:

- The floating mechanism uses floodwater's natural energy to raise the whole house without any other energy consumption.
- The column-and-ring connection employs rollers rather oil or another lubricant. The column-and-ring units are exposed to the water during a flood, so this choice eliminates

any chance to create water pollution. Likewise, the backflow prevention valve stops untreated sewage flowing into the open water.

- The softwood timber frame, while primarily chosen for its light weight, is a renewable resource.

On the negative side, this design encourages increased development in floodplains. Development invariably changes the landscape. Beyond the direct interference caused by excavation, runoff and sediment transport is altered, too. Extensive development can actually increase the likelihood of flooding. Runoff and sedimentation is often unpredictable, meaning that a project situated in a floodplain warrants extra planning and caution.

9.2. Socio-economic environmental impacts

On the other hand, this design has mostly positive socio-economic environmental impacts. Because it is a new and unique design, it is likely to draw a lot of public attention. The predicted socio-economic impacts of our design are as follows:

- Help individuals reduce flood damage to their house and their property. In particular, homes in some rural places are generally left at a flood's mercy while the government focuses on protecting large towns and cities. This situation was visible in the team's trip to Kent, where the Leigh Barrier spares Tonbridge at the expense of the unfortunate Yalding villagers.
- Since the architectural layout is based on a normal house, traditional lifestyles are not disturbed.
- The FPH design enables development closer to rivers, with the associated benefits in recreation, transportation and commerce. As a result, the value of land rises and business opportunities emerge, possibly even tourism to view the Flood-Proof Houses.

10. Conclusion

10.1. Feasibility

At the beginning of this project, it is aimed to produce a design that is feasible from three perspectives: technical, commercial and environmental. Firstly, the FPH incorporates a simple and effective floating technique. Our casco, column and ring calculations include many conservative assumptions covering even severe flood conditions in the UK. Moreover, the existing houses in the Netherlands successfully showcase the practicability of flotation combined with a column-and-ring system. Secondly, from the cost analysis, it is estimated that the FPH is within 20% of the cost of a normal house. Taking into account potential savings from insurance premiums, repair costs, lost property, temporary relocation and the hassle of a flooded home, this value seems very reasonable. Finally, the negative environmental impacts are quite minimal. Admittedly, any development has an effect on nature. The FPH consumes slightly more land area than a traditional house due to its wide foundation, but it does not have any pollution or harmful material problems. The indirect consequences, such as sedimentation, warrant close examination. Like any potential construction project, environmental impacts deserve careful consideration at the planning level.

10.2. Benefits

Potential benefits exist for at least three groups: homeowners, developers and the government. For homeowners who choose to live in a flood-prone area, the FPH protects their home, property and individual safety. For developers, this concept is an attractive new business. There is a big potential market to exploit valuable land, because people always want to live near the water. For the government, the FPH provides another solution in its effort to protect the public from floods. People expect government action, and many residents have voiced complaints about the government's inactivity following the 2000-2001 floods. Massive flood defence projects become financially infeasible for small villages. In addition, the FPH design opens up new land to ease the growing space problem.

10.3. Drawbacks

New designs inevitably have some drawbacks. In the case of the FPH:

- The house price is higher because to cover the extra costs.
- The flood-proof system requires accurate construction. Specifically, the watertight casco and the column-and-ring units are difficult to build on site.
- Many uncertainties are present in this design, such as the sedimentation system. This is a unique design, so we cannot draw on experience from previous prototypes. Implementing such a design would necessitate thorough testing.
- The environmental impacts are also uncertain and need to be studied carefully.

10.4. Closing comments

The government has been building and improving public flood defences for several decades, but few improvements have been made to individual residences. With flooding likely to increase in frequency and severity, new alternatives are needed now more than ever. At the same time, overcrowding is making development in floodplains increasingly attractive. Despite the above drawbacks, our Flood-Proof-House design presents a feasible option in our ongoing struggle to tame nature. Technically, it is a conservative design reliant on dependable and safe materials. It is appealing to developers and homeowners, as it can accommodate varying external environments and architectural styles. Certainly, the benefits are considerable, especially financial ones because the potential market is huge. In general, flood-proof houses provide a challenging, though promising, concept that is worthy of continued research in the future.

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Acknowledgements

The project team is grateful for the valuable support from ICE’s R&D Enabling fund (2001), and the extra support from the Happold Trust and Buro Cripps. Dr. John Loveless and Mr. Phil Leonard from Bristol University provided valuable advice and help in the physical model making and testing of the FPH. Finally, gratitude is expressed to Mr. Roelof Bakker at ABC Arkenbouw, the Netherlands, for demonstrating their floating homes during the team’s site visit.