Pressure transient suppression in drainage systems of tall buildings.

Abstract

The suppression of pressure transients in building drainage systems is now much better understood due to the 17 years of work following the invention of the first drainage specific positive pressure transient attenuation device (P.A.P.A^{TM}) in 2000. This device dealt with low-amplitude, yet significant, positive air pressure transients (typically 100 mm water gauge). This research deals with the attenuation of much larger problematic air pressure transients found particularly in tall buildings. This research describes the development of a new technique for the attenuation of positive air pressure transient of approximately 2000 mm wg (20kPa), a pressure transient of such magnitude which is not uncommon in tall buildings and for which there is currently no means to alleviate. The performance of the new technique was validated by numerical simulation and full-scale test rig experiments. The full-scale test rig represented a 44 storey building drainage stack with a main stack diameter of 150 mm. The pressure wave generator used to apply the 2000 mm wg pressure transient consisted of a large accumulator compressor capable of delivering 270 litres of air at 10bar pressure. This resulted in a capacity of 2700 litres of air at atmospheric pressure delivered into the system within 0.2 s. The pressure waves were delivered via an automatic computer controlled valve. Results show that a prototype device using the new technique is capable of reducing the applied pressure transient by 88%, rendering it harmless and returning the system to normal operation in a matter of seconds.

Keywords: building drainage systems; tall buildings; modelling; prototype testing

A	flow/trap cross sectional area, m^2
c	acoustic wave velocity, m/s
f	friction factor
h	trap seal depth, mm
p	pressure, mm water gauge
t	time, s
D	pipe diameter, m
G	acceleration due to gravity, m/s^2
K	loss coefficient
Lp	line pressure, N/m^2
pp	Pipe period (m)
U	mean airflow velocity, m/s
L	distance, m
E	Young's Modulus
e	pipe wall thickness
γ	ratio of specific heat
ρ	density, kg/m^3
Δp	pressure rise, N/m^2
Δt	time step, s

Abbreviations

AAV	air admittance valve
wg	water gauge

Introduction and Background

Any fluid carrying system will be subject to local pressure rises in the form of transient pressures or surges due to the inevitable changes in flow conditions experienced by the system. The instances of pressure rise in building drainage systems (BDS) is more common since all flows are as a result of random discharges of unsteady flows from sanitary fixtures such as WCs, sinks, baths and showers. Another significant factor in relation to BDS is the fact that the system is designed to expel waste water from a building, yet the vulnerability of the system depends on its ability to cope with the significant airflows induced as a result of the shear force between the water falling in the main stack and an entrained central air core. This shear force sets up airflows with an attendant air pressure regime. It is these air pressure fluctuations which designers try to avoid in the design stage (Swaffield, 2010).

Air pressure waves within the BDS

While every attempt is made to limit the air pressure surges in the BDS design process, transient air pressure waves will always occur and will propagate throughout the system at the local acoustic velocity (344 ms^{-1}). The effect of these air pressure waves can be devastating: sucking out water trap seals when the transient is negative (induced siphonage) or blowing the water trap into the room when the pressure transient is positive (Swaffield *et al* 2005[a,b]). The consequences of this occurrence are that the main seal between the habitable space inside the building and the main sewer is lost, leaving a direct route for the ingress of foul air into the building.

The ingress of malodourous air into a building may be bothersome and unpleasant, however there is a far more dangerous aspect to this breach in seal. Recent work has shown that the turbulence in building drainage system water flows is sufficient to aerosolise bacteria which can then be carried on BDS airflows and emerge into the building by trap seal breaches caused by excessive air pressure transients (Gormley *et al.*, 2017[a,b], Gormley *et al.*, 2013, Gormley *et al.*, 2012, Hung *et al.*, 2006). The work by Gormley *et al* (2017[a]) is particularly significant in that the article proved that cross contamination between different parts of a building could occur where there were empty water trap seals. The work showed that under normal operating conditions the unsteady discharge from a WC into the drainage system was sufficient to aerosolise bacteria (*Pseudomonas Putida*, a harmless bacterium was used) thus creating the correct conditions for pathogen transport on naturally occurring updrafts. The work also identified pressure transients as a cause for empty water trap seals and presents evidence of their occurrence, together with a tool for assessing the risk of disease spread. While this work is relevant to all buildings, it is particularly pertinent to hospital buildings where there may be a concentration of immune suppressed patients, and tall buildings where the risk of pressure transients is greatest.

The invention of the first ever positive air pressure transient attenuator designed specifically for use in building drainage systems in 2001 (Swaffield *et al* , 2005[a,b]), provided a significant new design option to engineers and architects faced with limiting the low amplitude air pressure transients likely to be found in these systems. This device was designed to cope with low amplitude pressure transients with a peak positive pressure up to approximately 100 mm wg (1kPa), with options for increasing this by adding two or more devices in series. It should be remembered that most water trap seals are 50 mm deep (with WCs 75mm deep) and so these water trap seals are vulnerable to any pressure transient in excess of 75 mm. These low amplitude air pressure transients are generated from momentary occlusions to the passage of air caused by a confluence of water flows within the building drainage system or temporary surcharge in the main sewer. In general, these events are fleeting, however they can create low amplitude air pressure transients of sufficient magnitude to cause breaches in the trap seal.

The growing number of tall buildings

The number of tall buildings being constructed around the world is growing rapidly. Whilst the definition of what constitutes a ‘tall building’ is subjective due to its relative height and proportion in comparison to its setting, a building of more than 50 m (or 14 floors) in height is typically used as the lower threshold. A building over 300 m (or 84 floors) in height is classed as a ‘supertall building’, and over 600 m (or 168 floors) in height is classed as a ‘megatall building’ (CTBUH, 2016). Although the number of floors can vary due to the changing floor to floor height between different buildings, these are stated here as an important comparator in terms of BDS design. A floor to floor height of 3.6 m has been assumed to correlate with that used by the Council on Tall Buildings and

Urban Habitat (CTBUH, 2016). In 2016, 128 buildings of 200 m height or greater were completed, 10 of which were classed as supertall. The total number of buildings of 200 m height or greater around the word is now 1,168 (a 441% increase from the year 200, when just 256 existed), with numbers expected to grow each year.

National Codes

National codes provide essential guidance for the design of building drainage and vent systems which, in the main, ensure the basic objectives of preventing odour ingress and cross-transmission of disease through trap seal retention. However, there are no specific design guide for BDS design for tall buildings and so the same codes and nethds are used for a 168 floor building as would be used for a 14 floor building.

Some of the commonly used national codes include the UK code (BS EN 12056-2:2000), the Australian and New Zealand code (AS/NZ 3500.2:2003), and two codes from the USA (the Uniform Plumbing Code [UPC 1-2003-1] and the International Plumbing Code [IPC]). The historic development of these codes (including their interpretation of the governing fluid mechanics principles and the degree of safety built-in) mean that many design differences exist between these national codes. For example, the UK code accepts trap seal depletion of 25%, i.e. 37.5 mm minimum retention for a 50 mm trap seal, whilst the Australian and New Zealand code accepts a minimum retention of 25 mm. Furthermore, the recommended interval between cross-vents linking the wet stack to the vent stack differs considerably between codes: 1-floor interval (UK code and Australian and New Zealand code); 5-floor interval (USA code – UPC); and 10-floor interval (USA code – IPC). The codes also differ in the size and scale of the systems they cover and most make no allowance for the specific building drainage design requirements of tall buildings on the scale of supertall or megatall buildings.

Table 1 compares the maximum number of theoretical floors that each code allows. For each case, a version of the traditional *modified one-pipe system* was assumed (having a wet stack and separate vent stack linked to the stack vent). To allow an illustrative comparison, the maximum number of theoretical floors was calculated in two ways depending on the design format of each code. In the UK code, the limiting factor on system size is given as the maximum hydraulic capacity for each stack diameter, whilst the other codes provide maximum discharge unit (DU) or fixture unit (FU) loadings as well as maximum allowable vent lengths.

Table 1: Maximum number of theoretical floors allowable in different national codes

	UK	AS/NZ	USA [UPC]	USA [IPC]
Stack diameter (DN)	200	150	200	250
Vent diameter (DN)	100	150	200	250
Maximum DU or FU	+1521	700	3600	4000
Maximum vent length (m)	-	300	228	*293
No. of Floors	**241**	**83**	**63**	**81**

+calculated using Equation 1
*stated as 960 feet in the code (1 foot = 0.3048 m)

Starting with the UK code, the expected waste water flowrate at any point in the system is determined from:

$$Q_{ww} = K\sqrt{\sum DU} \tag{1}$$

where Q_{ww} is the waste water flowrate (l/s), K is frequency factor, and ∑DU is the sum of discharge units specified for each sanitary appliance connected to the system. In order to calculate the maximum number of theoretical floors, Equation 1 was first rearranged to allow ∑DU to be calculated from the maximum hydraulic capacity (27.3 l/s) for the largest stack diameter (200 mm with 100 mm vent stack). When assuming a frequency factor of 0.7 (frequent use, e.g. hospital, school, restaurant, hotel), the maximum hydraulic capacity correlates with a total of 1521 DU. Dividing this with the number of discharge units for a typical apartment (basin [5.0 DU], bath [0.8 DU], shower [0.6 DU], wc [2 DU], sink [0.8 DU], washing machine [0.8 DU], and dishwasher [0.8 DU] = 6.3 DU), gives a maximum number of theoretical floors 241 (surpassing the 168 floor threshold for a megatall building).

For each of the other codes, the maximum vent lengths were identified, together with the corresponding maximum DU or FU loadings, and correlated with the specified stack and vent diameters. To convert maximum vent length to maximum number of theoretical floors, each was divided by the assumed floor to floor height of 3.6 m referred to earlier. This results in the 300 m maximum vent length in the Australian and

New Zealand code equating to 83 floors (matching the supertall building threshold but not allowing for higher), the 228 m in the USA [UPC] code equating to 63 floors (falling considerably short of the supertall building threshold), and the 293 m in the USA [IPC] code equating to 81 floors (just calling short of the supertall building threshold). Interestingly, the stack and vent diameters correlating with these system extremes also differ between codes, ranging from 150 mm in the Australian and New Zealand code, up to 250 mm in the USA [IPC] code. Additionally, the UK code is the only one to recommend a vent stack diameter which is half the stack diameter, whilst the others recommend that the vent stack diameter matches the stack diameter.
It should be noted that for the USA [IPC] code, a greater maximum vent length of 1,040 feet (317 m) for a 3 inch (76 mm) stack is included in the code, however, the maximum FU loadings were restrictive. Therefore, the maximum vent length selected allowed maximum length with maximum loading.

There is clearly no specific codes which span the range of buildings being designed and built at present and planned for in the future. This is evident from recent work by Gormley *et al* (2107[b]) which gives a public health engineer's point of view on the issues associated with using existing codes on tall building design, particularly those associated with venting arrangements on the roof.

The analysis of codes and standards and existing literature reveals that the pressure transient regime associated with tall buildings cannot be dealt with using existing design practices alone**.** In addition to the design issue there is growing evidence of the occurrence of very large air pressure surges in super high rise buildings, defined here as over 50 storeys tall. (Swaffield, 2010). One specific case in a high rise housing block in Hong Kong recorded positive pressure transients sufficient to blow water out of a WC pan some 2 metres into the air in the bathroom (Swaffield, 2010). These transients were caused by surcharges in the main sewer producing high magnitude pressure transients i.e pressure surges of sufficient magnitude to blow water from a WC some 2 m into the air and travelling at the local acoustic velocity (344 m/s) thus causing significant ongoing issues in housing apartments. Further anecdotal evidence gathered by the authors refer to pressures transients sufficient to lift manhole covers adjacent to buildings. Unlike low amplitude air pressure transients, these large air pressure waves are usually generated at the BDS/sewer interface. Other likely causes are offsets in the main vertical stacks, which should be avoided in the design.

Aims and Objectives

The aim of this research was to develop the necessary understanding of air pressure surges within the building drainage system of tall buildings in order to develop a practical solution to alleviate such pressure transients which would be suitable for installation within a building. This aim was achieved by addressing the following objectives:

- Develop a methodology for the simulation of large air pressure surges in tall buildings
- Establish optimal design of test rig using numerical modelling
- Construct new test rig
- Evaluate attenuation device

Theoretical basis for attenuating air pressure transients

Air pressure waves in BDS are due to sudden changes in airflow brought about by some occlusion of the route available to the passage of air. Changes in the annular water flow therefore continuously generate low amplitude air pressure transients whose magnitude are determined by the Joukowsky expression (Joukowsky, 1900):

$$\Delta p = \rho c V \qquad (1)$$

This fundamental equation relates the magnitude of the pressure transient (Δp) to the velocity of the fluid being stopped (v), the density of the fluid (ρ) and the wave speed (c) of the fluid.

The basis for attenuating air pressure transients in BDS is now well established (Swaffield *et al* 2005[a,b] and Swaffield, 2010).The principles are based on diversion of the pressure wave, the attenuation of wave speed in a containment volume, and the slow release of the pressure wave back into the vertical stack. The mechanism of pressure wave diversion is based on the rules of transmission and reflection as shown in Figure 1 for the analysis of a three-pipe junction;

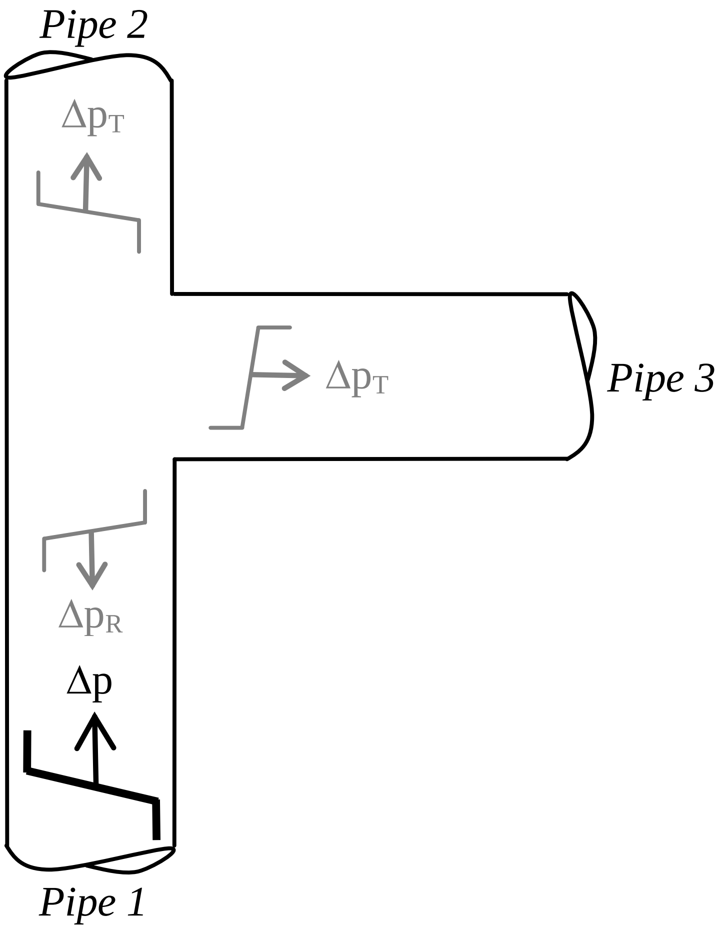

Figure 1: Division of an incoming air pressure wave (Δp) at a three-pipe junction into its transmitted (Δp_T) and reflected (Δp_R) parts

The transmission coefficient (representing the proportion of the wave that will be transmittes into Pipe 2 and Pipe 3) and reflection coefficient (representing the proportion of the wave that will return along Pipe 1) of a pressure wave arriving at a junction are given, respectively, by:

$$C_T^{junction} = \frac{\frac{2A_1}{c_1}}{\frac{A_1}{c_1} + \frac{A_2}{c_2} + \frac{A_3}{c_3} + \ldots + \frac{A_n}{c_n}} \quad (2)$$

$$C_R^{junction} = \frac{\frac{A_1}{c_1} - \frac{A_2}{c_2} - \frac{A_3}{c_3} - \ldots - \frac{A_n}{c_n}}{\frac{A_1}{c_1} + \frac{A_2}{c_2} + \frac{A_3}{c_3} + \ldots + \frac{A_n}{c_n}} \quad (3)$$

It should be noted that wave speed (*c*) features in both of these equations, however, in the simple case of a three-pipe junction for a rigid pipe then the wave speed will be the same everywhere and the only important factor will be the cross sectional area (*A*) of the pipe. However, as explained in the following section, wave speed is an integral parameter of pressure transient attenuation.

Significance of wave speed on attenuation

A closer look at the defining equations for wave speed in a pipe reveals that the pipe wall properties, and hence materials are critical.

$$c = \sqrt{\frac{\gamma P}{\rho\left[1 + \frac{\gamma P D}{E e}\right]}} \quad (4)$$

c	wave speed
γ	ratio of specific heat
P	pressure
ρ	fluid density
D	pipe diameter
E	Young's Modulus
e	pipe wall thickness

Therefore the material of the pipe wall is significant. A rigid pipe wall provides no change in wave speed, whilst an elastic pipe wall will produce a significant reduction in wave speed. From equations 2 and 3 it can be seen that the proportion of the wave diverted can be greatly increased by changing the wave speed of the branch (Pipe 3). The property most affecting the wave speed, as given in equation (4), is the Young's modulus:

$$E = \frac{tensile stress}{tensile strain} = \frac{\sigma}{\varepsilon} = \frac{F/A_o}{\Delta L/L_o} = \frac{FL_o}{A_o \Delta L} \tag{5}$$

E Young's Modulus

F applied force

A_o material cross sectional area

ΔL change in material length

L_o original material length

The range of values for *E* for a range of materials is shown in Table 1. Generally higher values represent more rigid materials and result in a minimal change in wave speed.

Table 2: Values of Young's modulus for a range of materials (Ugural, *et al*., 2011)

Material	Range (GPa)
Stainless steel	200-215
Cast Iron	80-160
Copper	107-130
Aluminium	69-70
Glass	68
Reinforced concrete	30-60
PVC Plastic	2.4-3.3
Synthetic rubber	0.0007-0.0083

Another important aspect to any change in wave speed is the thickness of the pipe wall. Figure 2 shows the calculated change in wave speed for a range of pipe wall thickness/pipe diameter ratios.

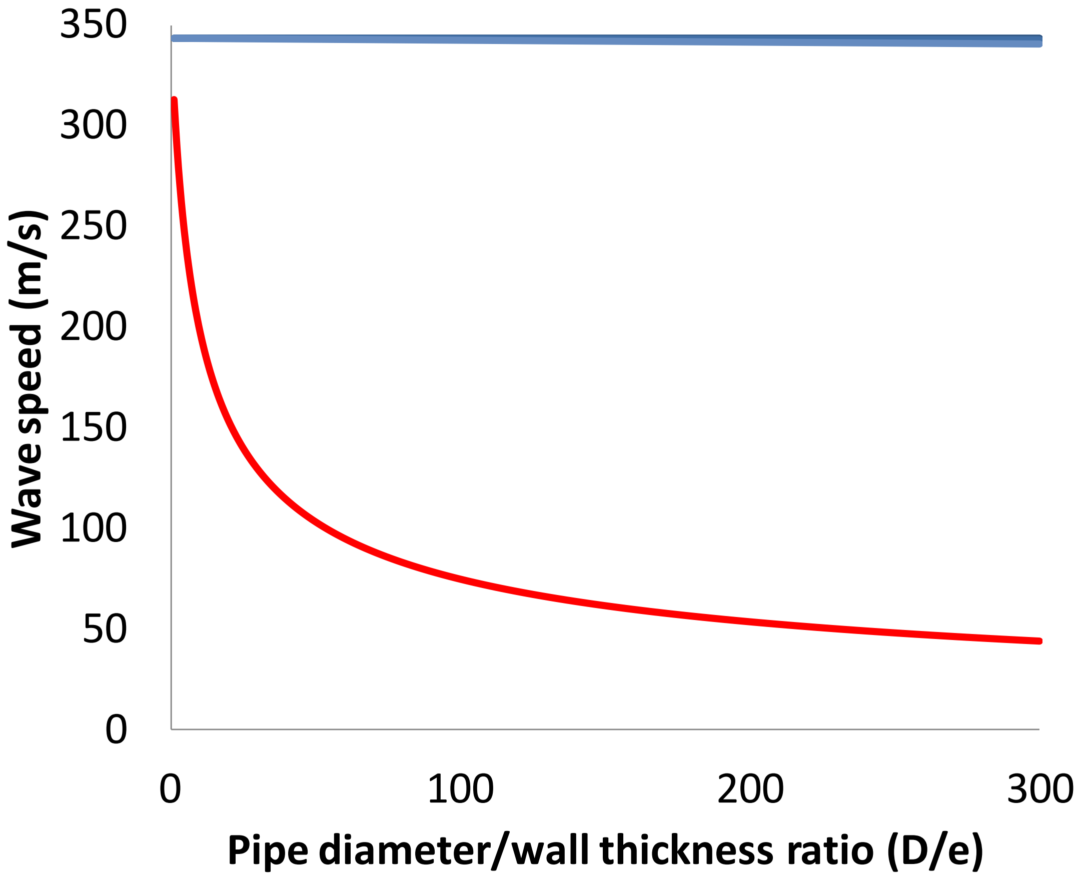

Figure 2. Calculated wave speed values for a range of pipe diameter/pipe wall thickness ratio. Note that rigid materials do not result in any reduction in wave speed.

Referring to equations 2 and 3 again reveals that the proportion of the wave diverted and transmitted, also depends on the cross sectional area of the exit branch. Figure 3 shows the transmitted wave for a range of branch to stack area ratio in relation to the number of junctions traversed

. This information is translated to a percentage of cross sectional area for the exit for the same range of branch pipe diameters in Figure 4.

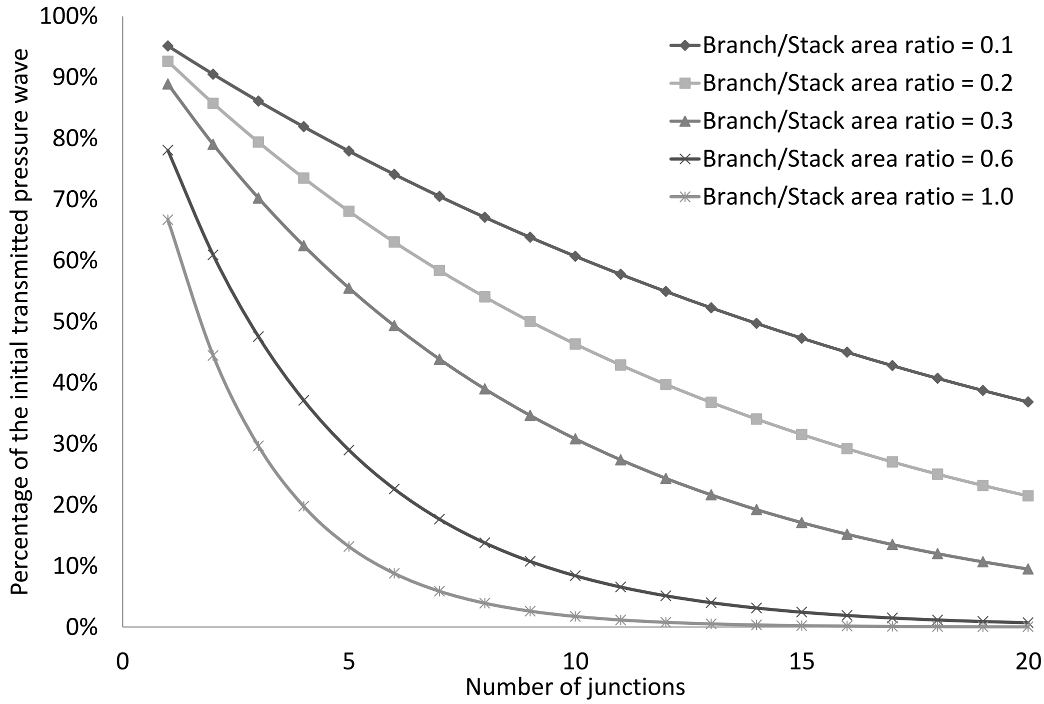

Figure 3. The relationship between branch to stack area ratio, number of junctions traversed, and the resultant proporation of transmitted pressure wave

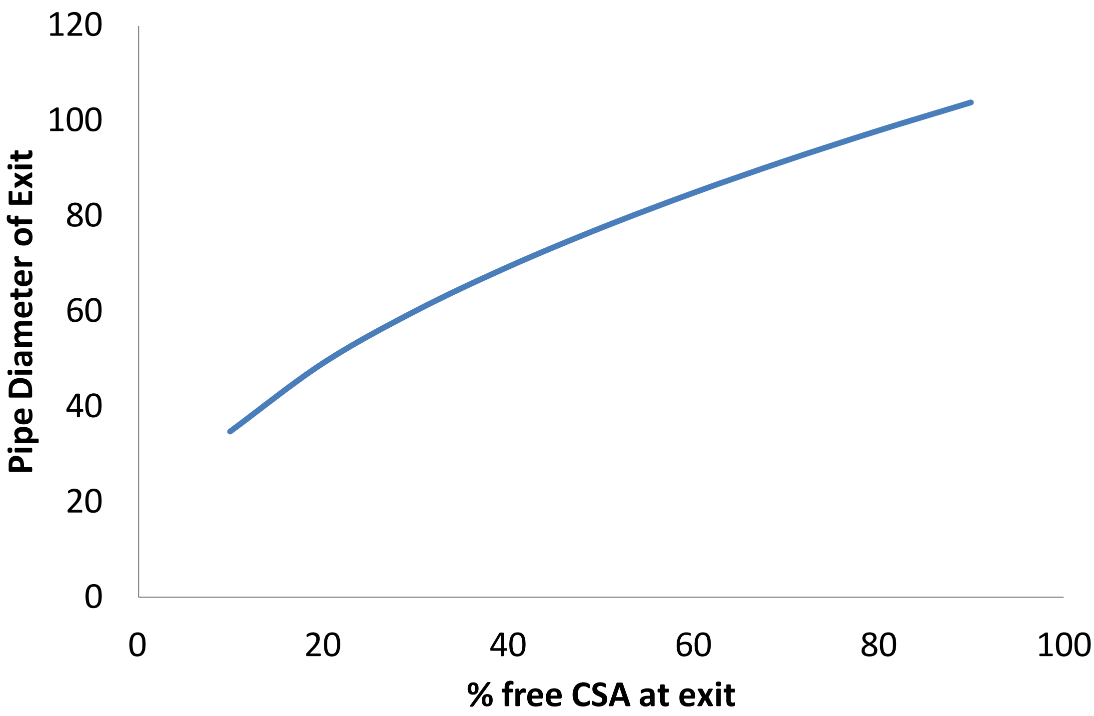

Figure 4. Percentage free cross-sectional area at the exit for a range of pipe diameter exits.

A discussion of the mechanisms of generation, transmission and reflection of air pressure waves in BDS leads to an understanding that the important properties relating to attenuation are the materials used and the proportion of cross sectional area available for diversion of the wave. A combination of diversion and change in wave speed results in an attenuation of the wave in the direction of travel. Choice of materials and dimensions of exist require a compromise between maximizing effective exit cross sectional area and structural integrity of the system

Methodology

This research seeks to establish a novel method for the alleviation of very large air pressure transients in the building drainage system of tall buildings. The methodology employed focuses on two main investigative techniques: numerical simulation of an ideal attenuator and establishing operational parameters for the physical model and the construction of a full scale physical model. The numerical simulation was carried out in the 1D finite difference, method of characteristics model known as AIRNET, which has been developed at Heriot-Watt University over the past

30 years. The program was instrumental in the design and evaluation of the first ever air pressure transient attenuator. In addition to the use of AIRNET to simulate the operation of an ideal attenuator, a full scale physical model was used to assess the effectiveness of the developed solution using a horizontally mounted 160 m (equating to a 44 floor building) The physical model used air only. This methodology was first used to develop the first air pressure transient attenuator (see Swaffield *et al* 2005b for full detail). Since the product developed using this methodology has been used in buildings safely for nearly 15 years the methodology has been proven to be an effective representative model for the generation and propagation of air pressure transients in building drainage systems.

AIRNET simulations: establishing criteria for the ideal attenuator

The AIRNET program simulates the propagation of low amplitude air pressure transients using the fundamental St. Venant equations of motion and continuity and by the numerical solution of these equations, via the method of characteristics. The method is used to yield air pressure and velocity within a duct system subjected to air pressure transient propagation. (Swaffield and Campbell, 1992[a] and 1992[b], Swaffield and Boldy, 1993). As the air pressure and density are linked, the defining finite difference equations have to be recast in terms of air velocity and wave speed.

Entrained airflow analysis.

The basic principles governing the model's operation can be seen by looking at the example of an entrained airflow analysis as illustrated in Figure 5 As water enters the stack from a branch, an airflow is entrained into the network and leads to a suction pressure in the vertical stack. Pressure drops are experienced at the termination at the top of the stack due to separation losses associated with the method of termination the airflow passes through (AAV or open end). Frictional losses in the dry stack lead to a further pressure drop and can be calculated from an application of D'Arcy's equation. A further pressure drop is evident as the water from the branch forces its way through the air core.

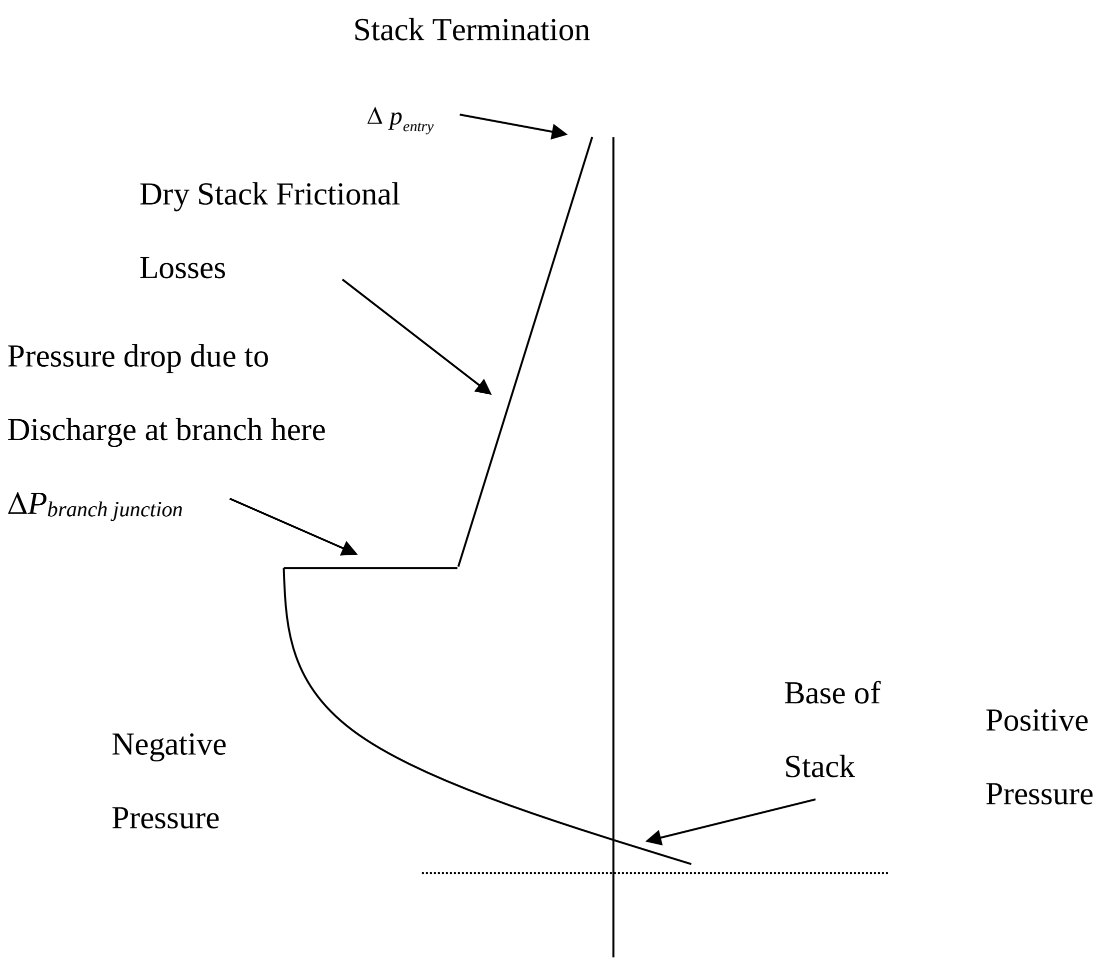

Figure 5. Entrained Airflow Analysis for AIRNET Model

Figure 5 also shows the positive pressure at the base of the stack as the airflow is forced through the water curtain formed at the bend at the base of the stack (this is not to be mistaken for a positive pressure transient which will propagate through the system at the local acoustic velocity) .

These pressure losses in the stack may be combined as

$$\Delta p_{total} = \Delta p_{entry} + \Delta p_{dry\_pipe\ friction} + \Delta p_{branch\ junction} + \Delta p_{back\ pressure} \qquad (6)$$

The 'motive force' to entrain this airflow and compensate for these `pressure losses' is derived from the shear force between the annular terminal velocity water layer and the air in the wet portion of the stack. This can be considered as a `negative' friction factor that generates an equal pressure rise to that determined from equation *6* - the equivalent to a fan characteristic drawing air through the stack.

In order to make use of this entrained airflow model a mathematical technique is required. The method of characteristics provides such a flexible mathematical model which can deal well with the representation of pressure transients in complex pipe and duct networks, and has become the standard solution technique applied to their analysis throughout the field.

The basic equations of transient theory, the St. Venant equations of momentum and continuity, may be shown to be a pair of quasi –linear hyperbolic partial differential equations that may be transformed into a pair of total derivative equations which can be solved by a finite difference scheme via the method of characteristics. The diagram in Figure 5 shows the grid representation of the scheme used for the calculation of the propagation of pressure transients along a pipe.

The grid is formed in two dimensions, representing time, t and distance, x. The conditions at one point in the grid are based on the conditions upstream and downstream, one time step in the past and require a definition of the characteristic slope as a basis for calculation.

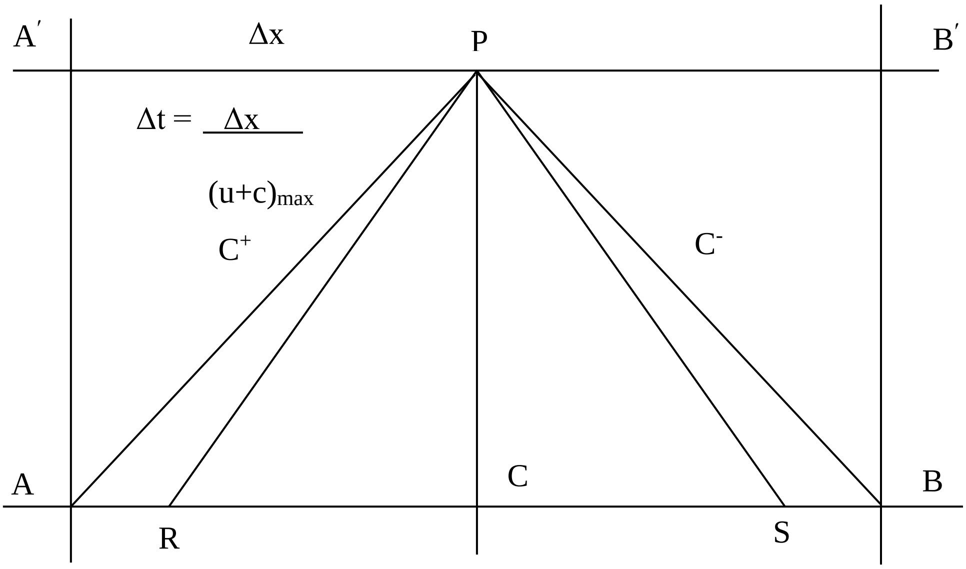

Figure 6 Grid showing characteristic lines as utilised in Method of Characteristics approach to air pressure transient modelling

Boundary Conditions

The technique described above requires the initial conditions to be known so that calculations can begin. It can also be seen from Figure 6 that while the pressure at P can be calculated from the characteristic equations C^+ and C^- based on the information known about A and B, a problem occurs at the pipe boundaries, defined as AA' and BB'. At a boundary only one characteristic is available, a C^+ at B' and a C^- at A'. In order for these nodes to be solved and the calculation to progress, boundary conditions compatible with a single C^+ and C^- characteristic are required. As there are always two unknown variables – fluid velocity and wave speed and only one characteristic equation at one time step approaching a boundary, the model therefore requires an additional equation to solve simultaneously for the variables. The boundary condition expressions must be representative of the physical restriction imposed on the flow at that particular point. Boundary conditions are therefore required at time step zero in order that the calculation can begin and boundary conditions are required for the network in order that calculations can progress. Figure 7 shows a range of building drainage components and their associated characteristic lines.

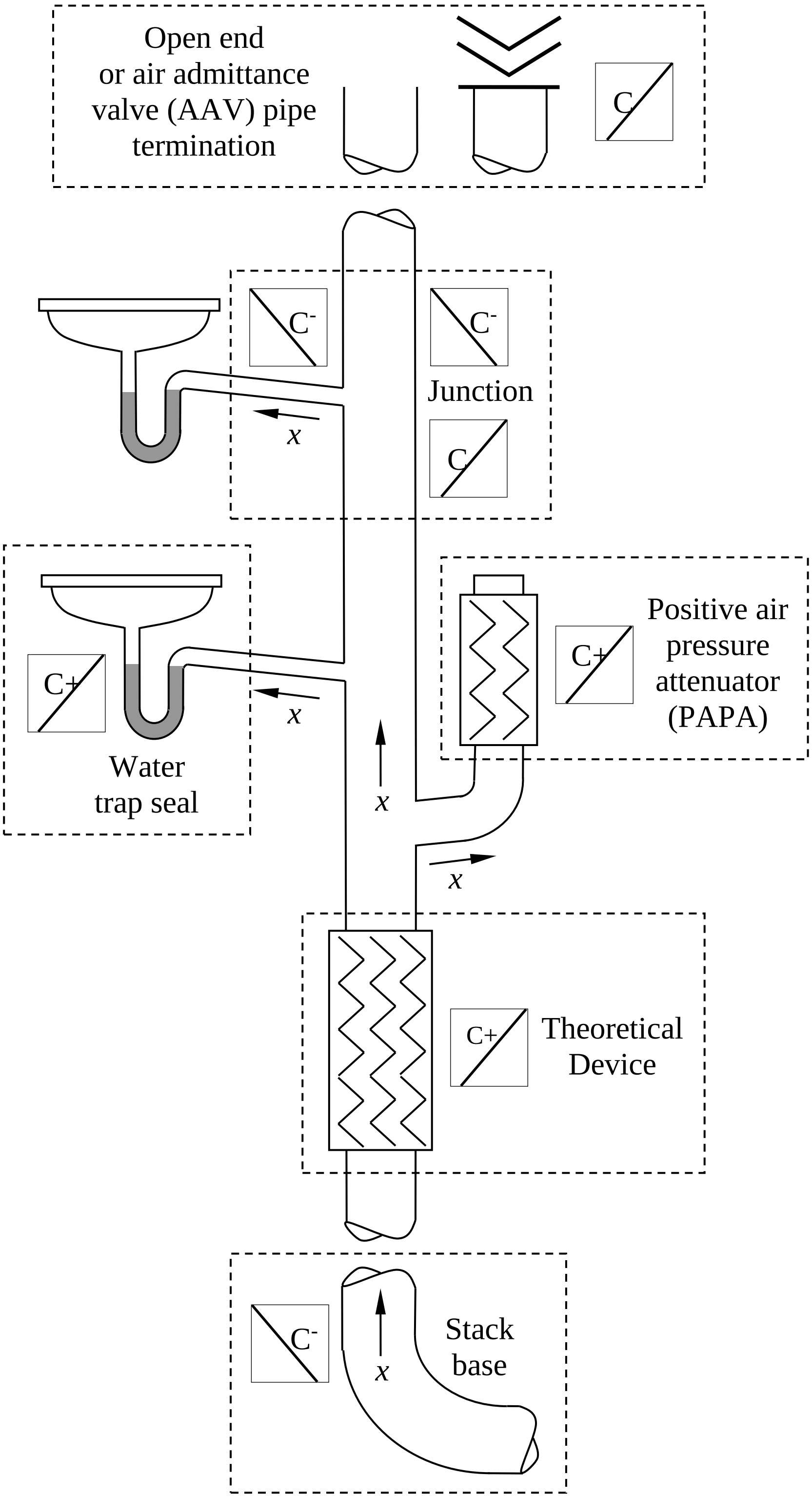

Figure 7: Boundary conditions and available characteristics for a typical building drainage system

A boundary condition for the theoretical device

The theoretical attenuator consists of a series of exits from the main stack pipe, such that air can leave the pipe in a linear fashion as shown in Figure 8, thus effecting a continuous attenuation.

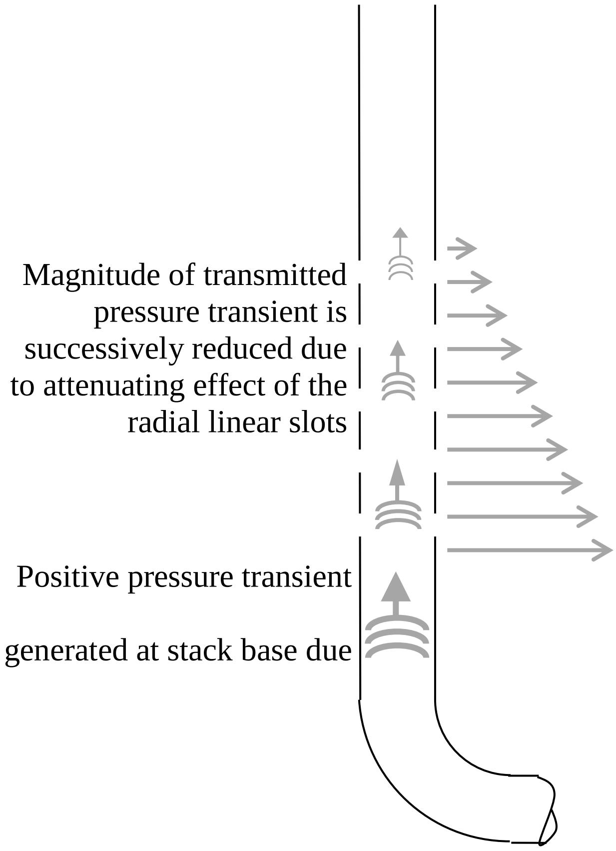

Figure 8: Pressure transient attenuating effect of theoretical device

A pressure transient alleviation device must be able to provide an alternative route along which a significant portion of the pressure wave can propagate away from the areas of the system to be protected. In effect, this key attribute disperses and attenuates the propagating pressure wave.

From Equation 3, it can be seen that the inclusion of any exit branch creates a junction along the vertical stack where the proportion of the propagating pressure wave, which is transmitted beyond the junction, is determined by the cross sectional area of the pipes creating the junction and the wave propagation speed within them. Furthermore, the greater the cross sectional area of the branch, the smaller the proportion of the pressure wave transmitted. Figure 3 illustrated the relationship between branch to stack area ratio, the number of junctions traversed, and the resultant proportion of the propagating pressure transient transmitted. The branch length is assumed to be sufficiently long (greater than the pipe period of the whole system) as to allow any reflections from branch terminations to be ignored. Therefore, for a branch to stack area ratio of 1.0, after traversing 10 such junctions, the transmitted pressure wave drops to just 2% of its original magnitude, a reduction of 98%.

The numerical model, AIRNET, was used to verify the assumed operation of the theoretical device. Figure 8 shows the simulated system. It has an 85m vertical stack with a diameter of 150mm. The ideal attenuation device was represented by ten 150mm diameter branches each 100m long and spaced 0.2m apart giving an overall device length of 3.3m. The length of the pipes are required to avoid any unnecessary reflections during the test run. An exit cross sectional area equivalent to 11.4% of a 3.3m stack section to which they are connected was modelled. Connected above the device are four 100mm diameter branches, each 2m in length, at 20m intervals.

The pressure wave is generated 3m below the device at the base of the vertical stack by a simulated piston with a diameter of 1.2m and a length of 0.5m, giving a piston volume of 565 litres. The piston dimensions were determined by trial and error with the aim of producing a pressure wave with a magnitude of around 2000mm wg (20kPa peak). The pressure wave is generated by moving the piston 0.228m in 0.384 seconds.

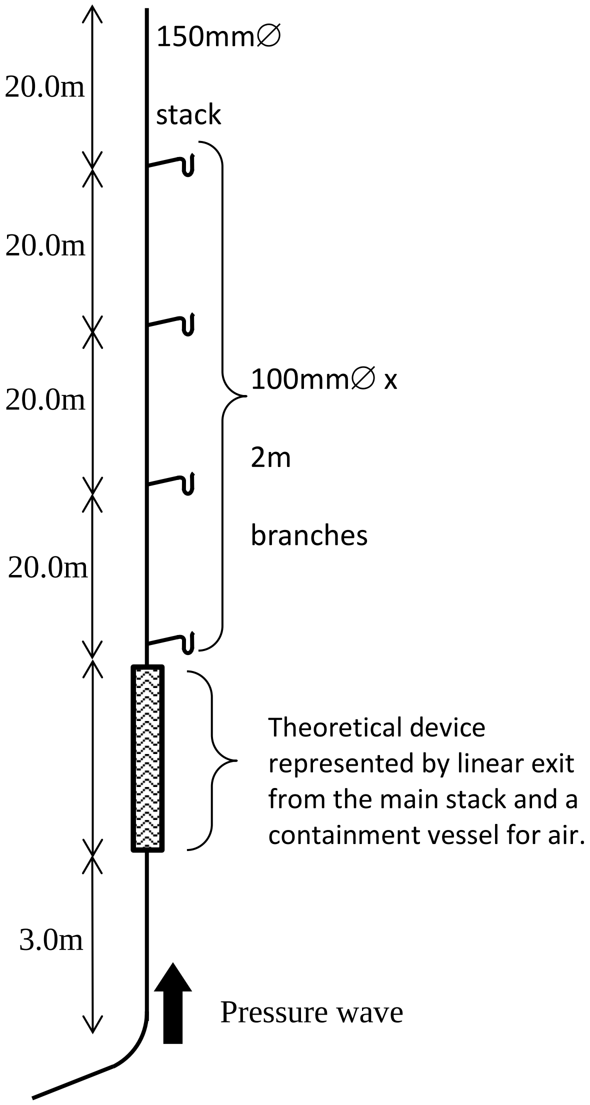

Figure 9: The system used to test the attenuating principles of the Inline Attenuator, based on junction transmission, using AIRNET

Figure 10 shows the pressure response of the system with and without the branch exits. Without the ten branches, the pressure wave reaches a peak of 2201.54mm wg. With the ten branches are connected, the peak pressure drops to 267.09mm wg, representing a drop of 88% to just 12% of the original wave.

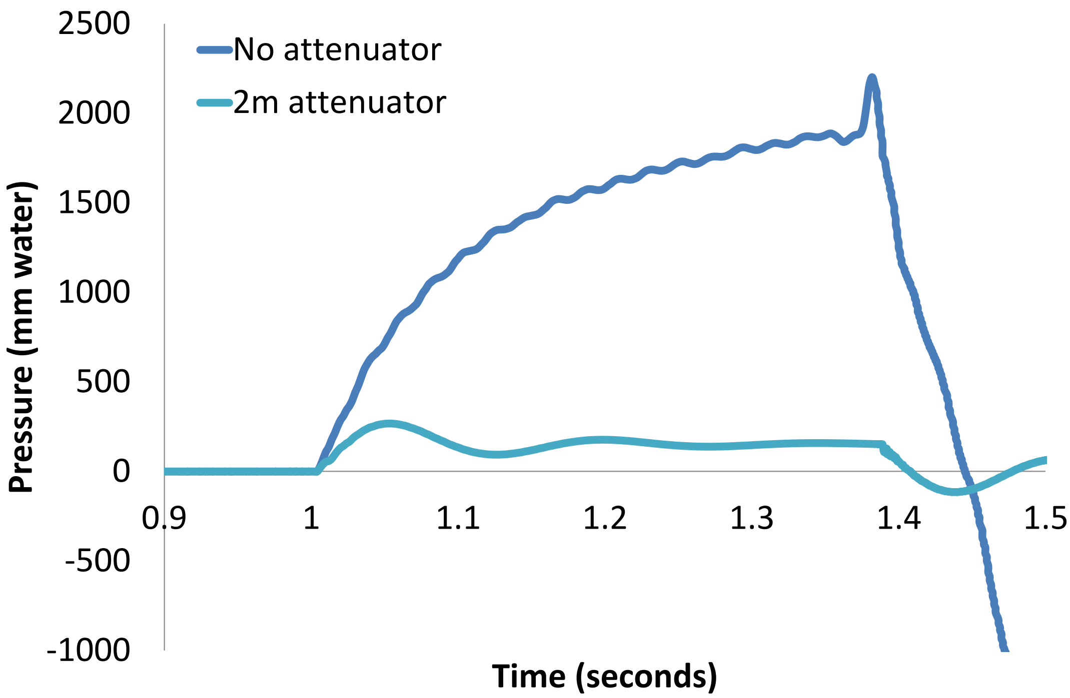

Figure 10: AIRNET simulated pressure response of the system shown in Figure 9 showing the attenuating effect of the linear exits.

These initial simulations confirm the hypothesis that the propagating pressure wave can be attenuated by providing an alternative route along which it can travel.

Full-scale test rig simulation: protoype testing

System setup and pressure generator calibration

The proposed device is designed to attenuate the pressures generated within the drainage systems of tall buildings. It is estimated that these pressures will be in the region of 2000mm wg .In order to generate such pressures under test conditions, an air compressor was used. AIRNET was used to establish timings for opening and closing valves. In this case, the piston was specified as 1.4m long x 0.5m diameter, giving an overall volume of 275 litres, matching closely with the 270 litres of the air compressor receiver. The distance over which the piston moved was set at the maximum of 1.4m.

Figure 11 shows the simulated pipe system. It can be seen that it consists mainly of 3 parts: Pipe 1 (piston/compressor); Pipe 2 (connection pipe); and Pipe 3 (drainage stack). To represent the vertical drainage stack of a 50-storey building, Pipe 3 was set to a height of 150m and defined as 150mm diameter uPVC pipe, with a pipe roughness coefficient of 0.06mm. The connection pipe between the compressor and stack, Pipe 2, was set as 2m long with a 50mm diameter.

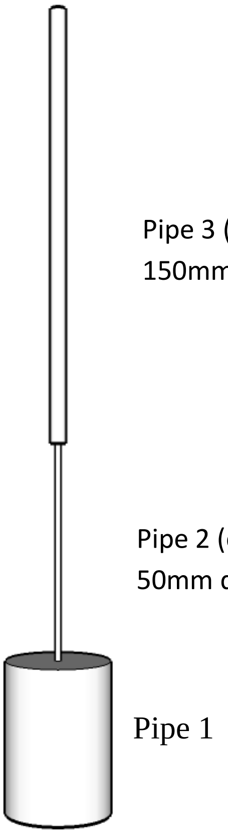

Figure 11: Simulated full-scale test rig in AIRNET : Used to establish limitations of operation of full scale test and optimum valve opening and closing time.

In the actual full-scale test rig, a valve would be used to release the air from the compressor into the drainage stack. The opening characteristics of the valve can be represented within the simulation by the movement of the piston. The time taken for the piston to move from its start position to its end position can be taken to represent the valve opening time. Valve opening times of 0.05 seconds, 0.5 seconds, 1.0 second, and 2.0 seconds were investigated. Figure 12 illustrates the resultant pressure response to the different valve opening times as monitored at the beginning of Pipe 3. It can be seen that the pressure response of the 0.5 second opening time is affected by considerable noise, while the 1.0 second and 2.0 second times give a cleaner pressure signal. However, these latter two opening times produce peak pressures of just 400mm wg and 900mm wg, respectively, which are both smaller than the desired magnitude of 2000mm wg. Despite the noise, it can be seen that the 0.5 second opening time does in fact attain this pressure. Therefore, options were investigated which would help to remove the noise from this pressure signal.

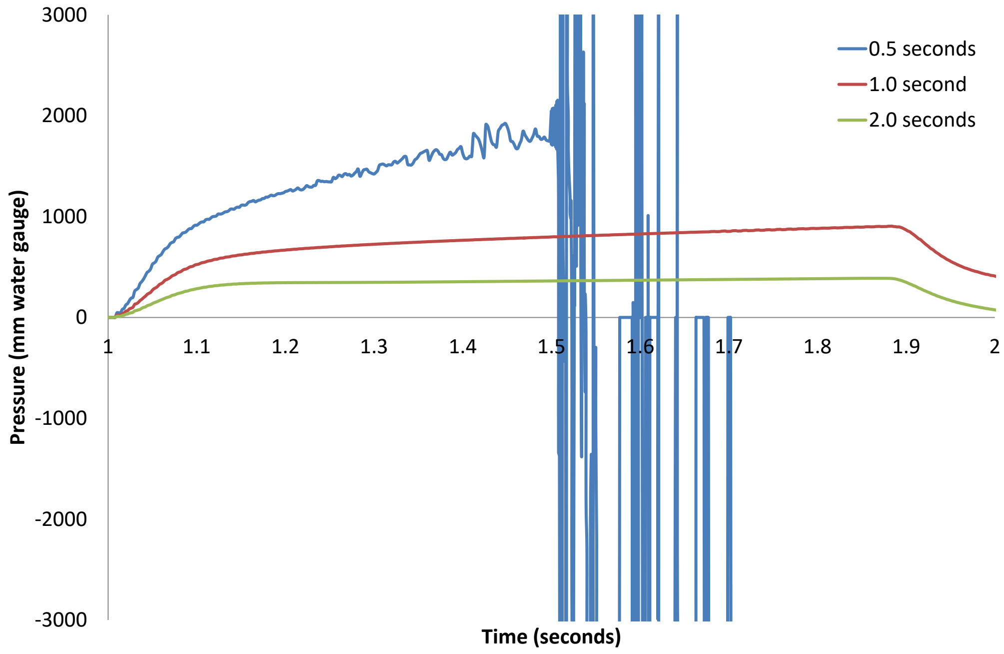

Figure 12: The effect of valve opening time on the form of the propagating pressure wave (measured at the beginning of Pipe 3)

It was found that increasing the diameter of Pipe 2 would improve the signal by removing the noise. In addition to the original diameter of 50mm, further diameters of 65mm and 100mm were investigated. Figure 12 shows that with each diameter increase, the resultant pressure signal is less affected by noise. The 100mm diameter connecting pipe provides a good clean signal while producing a peak pressure just below 2000mmwg. However, connecting a 100mm pipe to the actual air compressor would be met with a number of practical difficulties, discounting it as a viable option. A tapered pipe, increasing from a 50mm connection to the compressor to the full 150mm diameter of the drainage stack, was then tested. The tapered pipe not only provides a practical connection solution, but it also helps to generate a pressure signal which is both clean and of the right magnitude, see Figure 13.

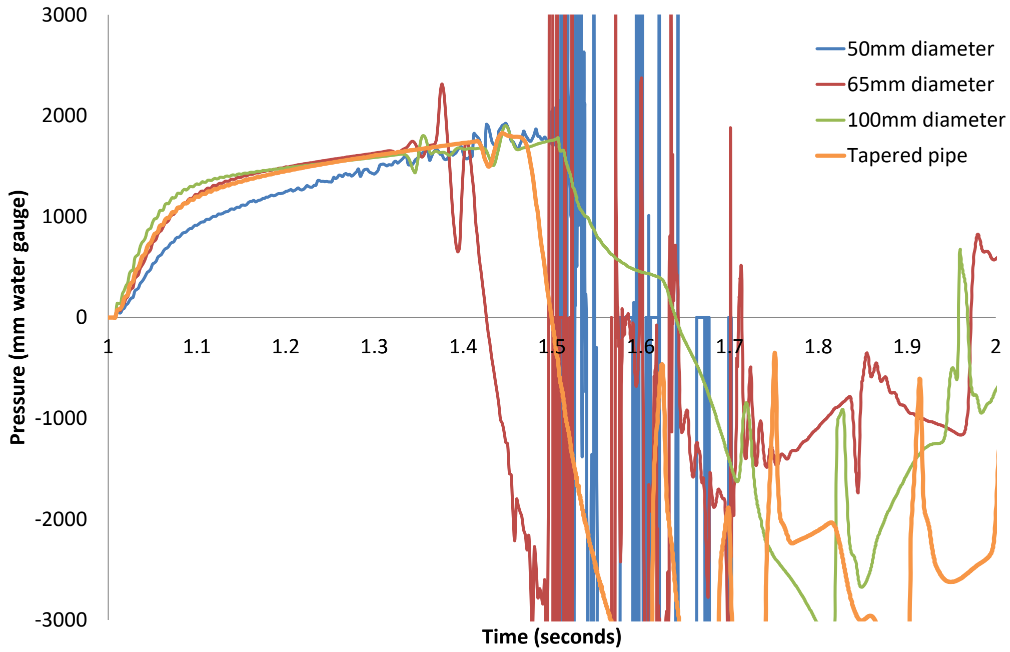

Figure 13: The effect of connection pipe diameter on the form of the propagating pressure wave (measured at the beginning of Pipe 3)

Full-scale test rig investigations: installation

As it was impractical to erect a 50-storey vertical stack, the test rig was designed as a simple looped system on the horizontal plane using HPPE pipe as shown in Figure 14. Electrofusion fittings were used for easy and fast assembly, and also for their high pressure rating. All pipework and fittings were rated to 10Bar as, although the tests would not use pressures of this magnitude, the compressor used to create the pressure wave had a maximum working pressure of 10Bar. The test rig consisted of looped sections of HPPE pipe, with a nominal diameter of 160mm and a wall thickness of 9.5mm giving an internal diameter of 141mm.. The total length of the pipe was just over 160m from the first pressure transducer, constructed in an inward loop with long radius bends (800mm radius). The pipe was fixed to free standing supports using rubber lined pipe clamps, spaced at regular intervals.

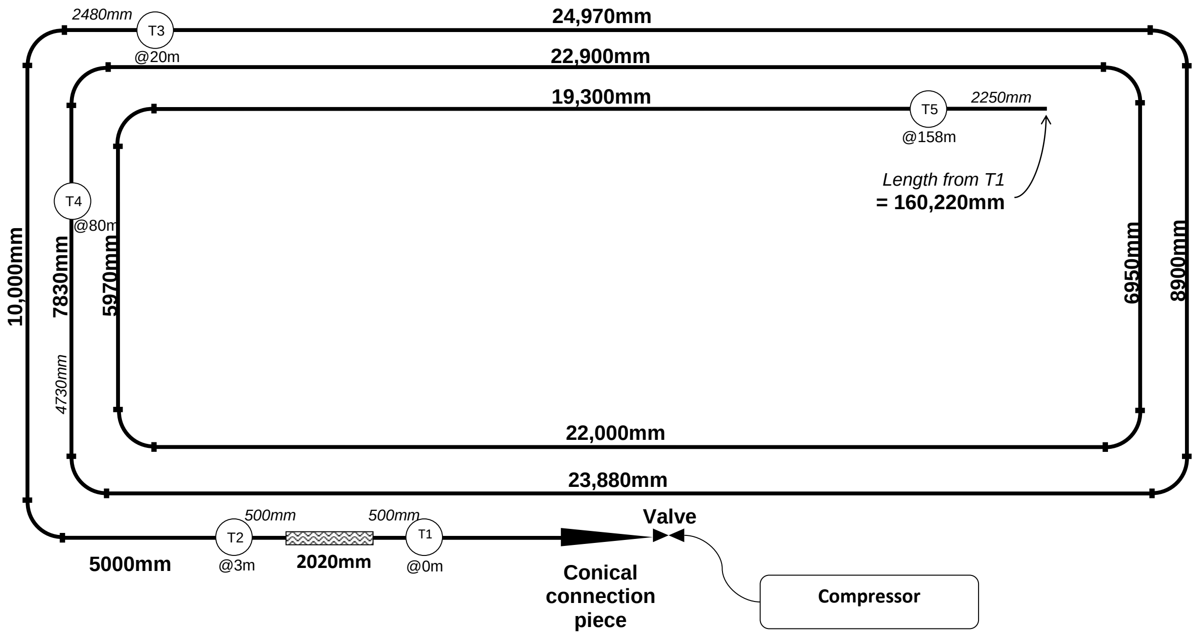

Figure 14: Full-scale test rig

An industrial duty air compressor (Clarke SE45C270) with a 270 litre horizontal air receiver and rated to a maximum working pressure of 10Bar was connected at the simulated stack base. A proportional control valve located just upstream of the compressor was used to generate the desired transient event. From the results of the simulation study, the valve was controlled to have an opening time of 0.5 seconds, a variable fully-open duration in order to allow control over the final test pressure, and a slow closing time of 5 seconds to avoid generating unwanted transients on closing, see Figure 15. To provide a smooth transition from the valve into the test rig, a conical connection piece was manufactured to replicate the tapered pipe designed during the full scale test-rig simulation work. The details of the conical connection piece can be seen in Figure 16.

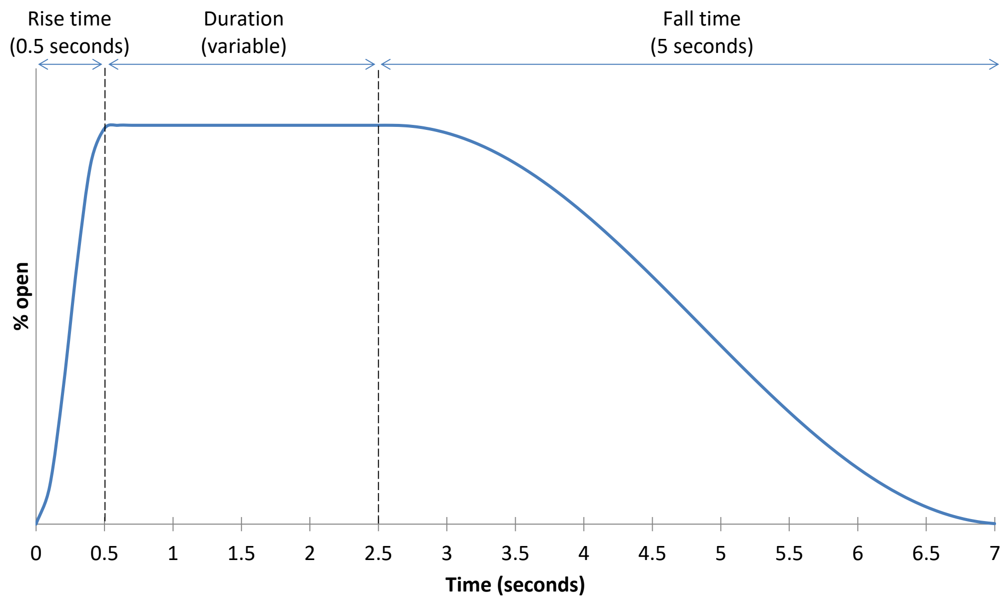

Figure 15: Valve control diagram

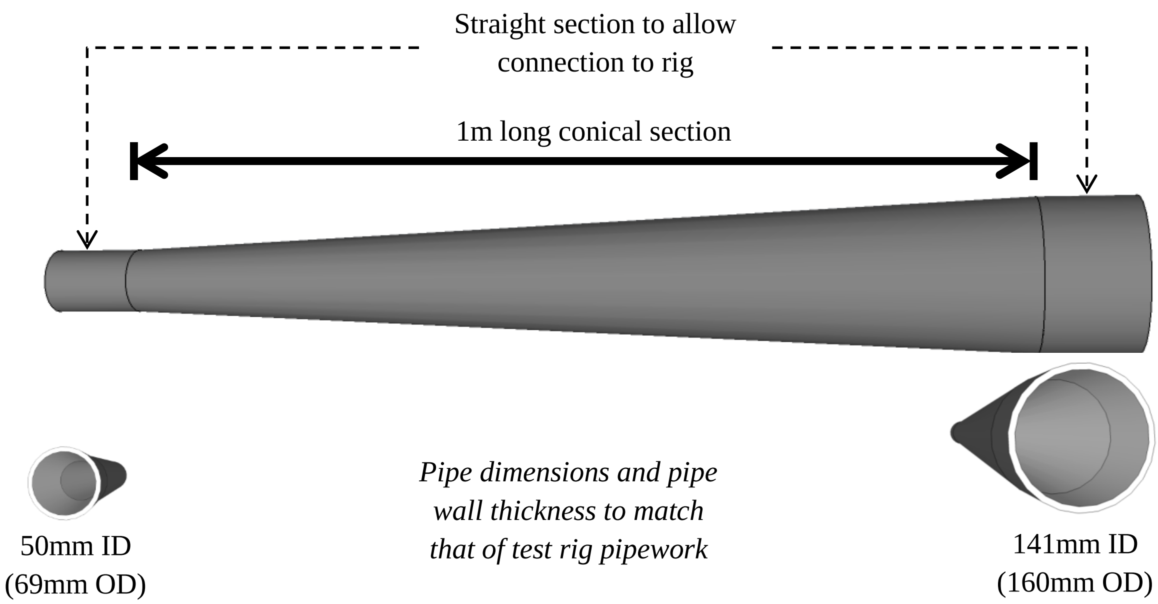

Figure 16: Conical connection piece used to deliver the pressure wave to the test rig.

Investigation of device opening area

Figure 17 shows the pressure response to the applied pressure wave, recorded at pressure sensor T1 (Figure 14). The effect of opening area was tested for comparison with the results from the laboratory investigations. Table 2 details the reduction in maximum peak pressure for each of the opening areas tested. With no device fitted , the maximum pressure peak can be seen to reach almost 2500mmwg. With just a 0.21% opening area, the maximum peak pressure recorded at T1 reduces to 511.5mmWG (79.2% reduction). Increasing the opening area had the corresponding effect of reducing the maximum peak pressure recorded within the system, although, as the opening area was increased in small increments (from 0.21% to 2.12%) the recorded reduction in maximum peak pressure was also small: 0.85% opening area (4 slots open) provided an 80.3% reduction; 1.27% opening area (6 slots open) provided an 80.8% reduction; 1.70% opening area (8 slots open) provided an 82.3% reduction; and the 2.12% opening area (all 10 slots open) provided an 88.1% reduction.

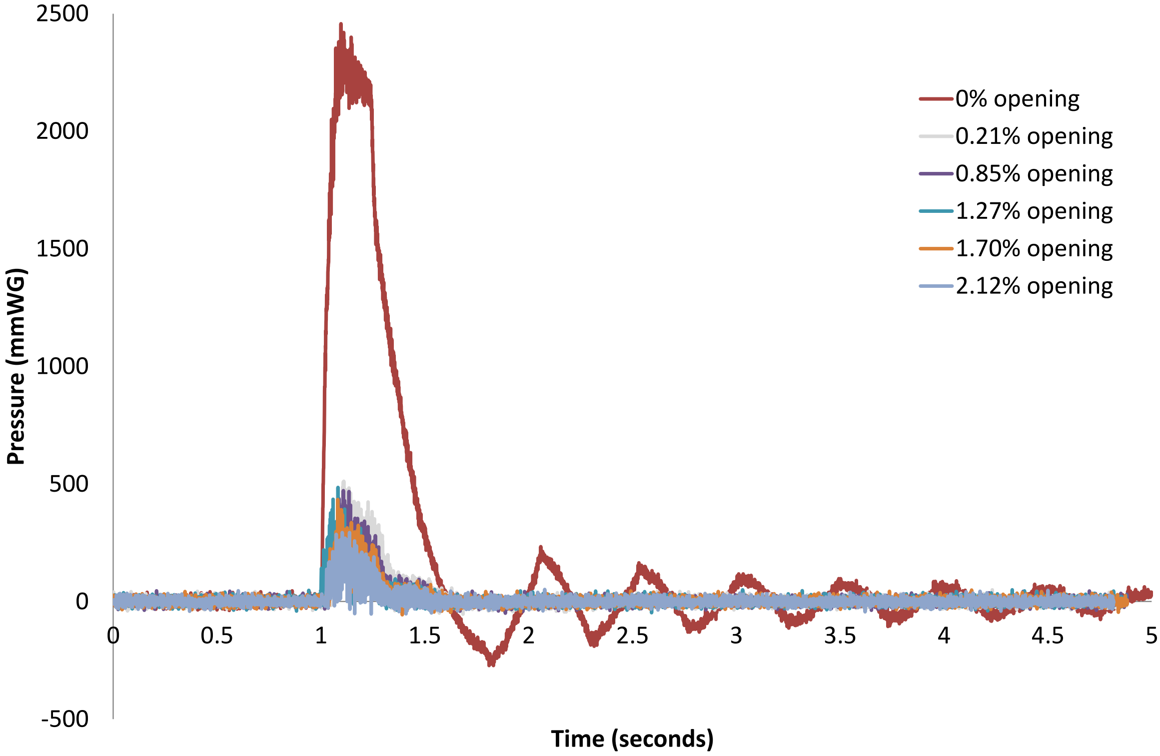

Figure 17: Measured pressure response from the test rig at pressure transducer T1 demonstrating the attenuating effect of different opening areas within the pipe surface.

Table 2: The reduction of maximum peak pressure attributed to the range of opening areas assessed on the test rig.

Opening length	Opening length	Opening area	Opening area	Max Peak Pressure	Reduction in Maximum Peak Pressure
Mm	(%)	mm2	(%)	(mmWG)	(%)
0	0.0	0	0	2457.1	0
140	9.4	1400	0.21	511.5	79.2
560	37.6	5600	0.85	485.0	80.3
840	56.4	8400	1.27	471.0	80.8
1120	75.2	11200	1.70	433.9	82.3
1400	94.0	14000	2.12	293.4	88.1

The relationship of opening area and maximum peak pressure reduction is illustrated in Figure 18 and shows that, similar to the results from the laboratory investigations, just a small opening area provided in the pipe surface can produce a significant reduction in maximum peak pressure. While these tests have assessed just small increments in opening area compared with those assessed in the laboratory, it can still be seen that the majority of the reduction in maximum peak pressure is achieved with just a small opening area and any additional openings see limited added benefit.

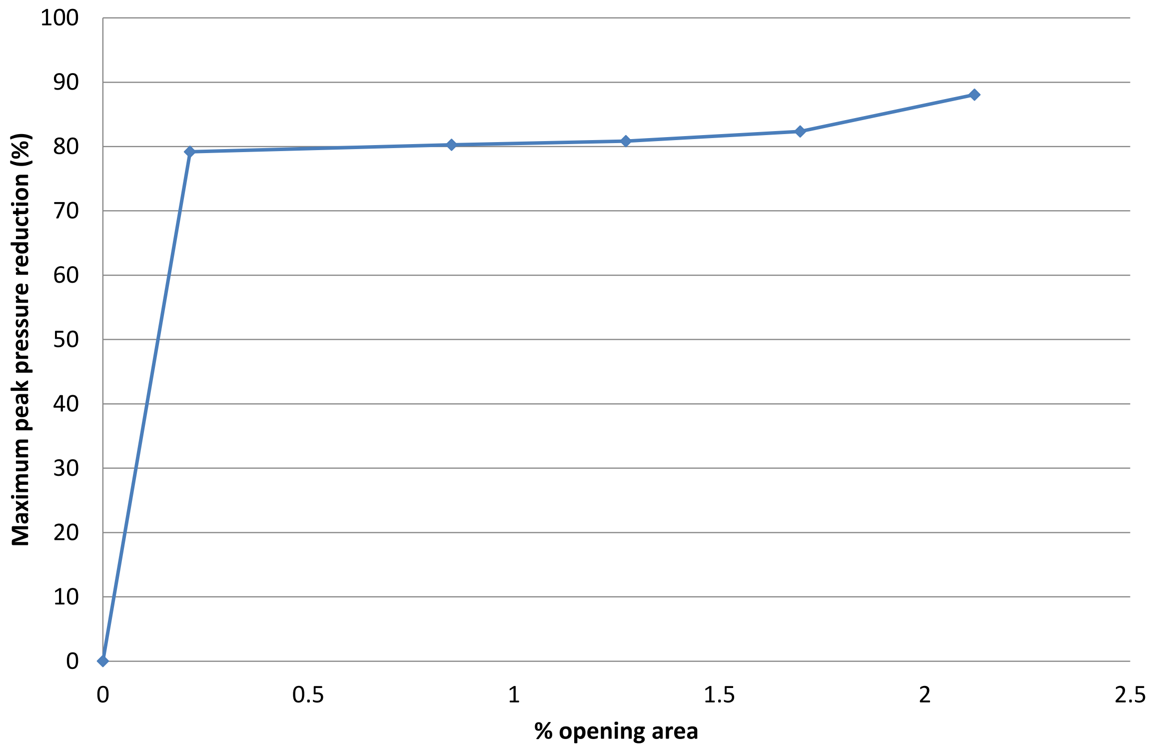

Figure 18: The reduction of maximum peak pressure as attributed to different opening areas assessed on the test rig

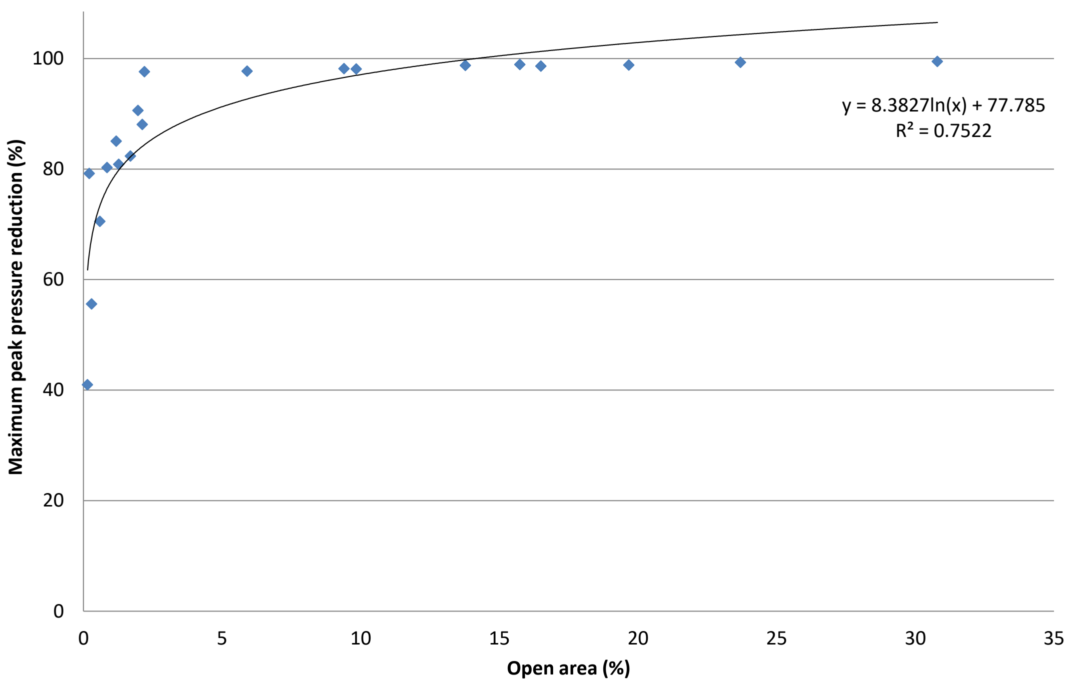

Figure 19: Device evaluation on full-scale test rig

While the first set of tests on the full size test-rig were based on a simple laboratory prototype, providing the propagating pressure wave with a route out of the system direct to atmosphere, it is of course necessary to provide a containment method whereby the air is kept within the drainage system. This is achieved by providing an additional volume with adequate capacity to absorb the propagating pressure wave. The containment volume was provided by creating a collapsible cylinder which was secured at either end of the linear exits . The collapsible cylinder was designed to give a maximum diameter of 500mm when fully inflated, providing an additional volume of 311 litres compared to the 23 litre volume of the pipe alone, an increase of almost 14 times. The system, which now includes a flexible conduit wall, also benefits from the attenuating effect of reduction in wave speed.

In addition to testing the pre-production device prototype for its ability to reduce the maximum peak pressure of an applied pressure wave, the direct effect on trap retention was tested by installing a WC onto the test rig. The WC was connected to the test rig via a 2m long 100mm diameter branch located 15 m (equivalent to 5 floors) from pressure sensor T1, see Figure 20. In order to avoid damaging the WC, the magnitude of the applied pressure wave was reduced slightly from the initial tests.

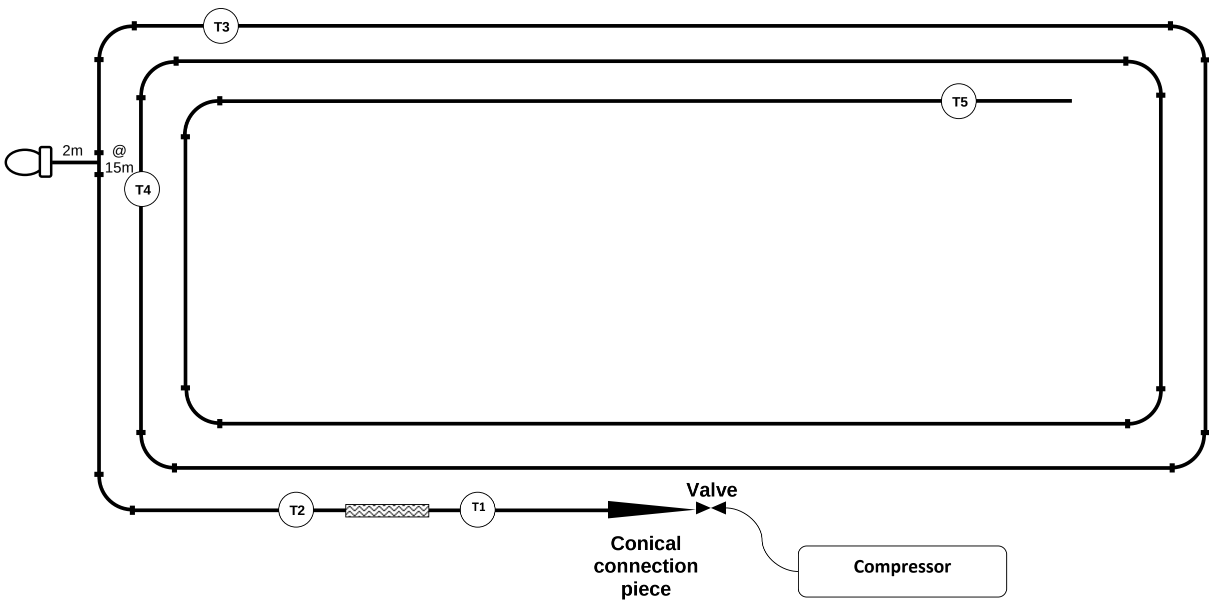

Figure 20: Full-scale test rig showing branch and WC connection

Figure 21 shows the pressure response to the applied pressure wave for the system with and without the device connected. Without the device the maximum peak pressure recorded was 1368mmWG. While the inclusion of the WC branch creates a junction within the system which has the effect of dividing the wave into reflected and transmitted components, from Equation 3, the proportion of the wave transmitted into the WC branch would be 80% of the propagating wave. Therefore, it can be assumed that a pressure wave of just under 1100mmWG is transmitted into the WC branch. Figure 21 shows the recorded pressures before and after the installation of the device. A pressure wave of this magnitude completely blew out the water trap of the WC, resulting in full loss (see Figure 22). In inclusion of the device reduced the maximum peak pressure to just 162mmWG, representing a reduction of 88%. Assuming 80% transmission into the WC branch, it can be assumed that a pressure wave of just under 130mmWG is transmitted. Although, still higher than recommended, instead of completely losing the trap the trap water was pushed into the WC bowl with sufficient water returning to provide an operational trap seal, and importantly the wave speed had been reduced with attendant reductions in volume of air which minimized the impact on the WC.

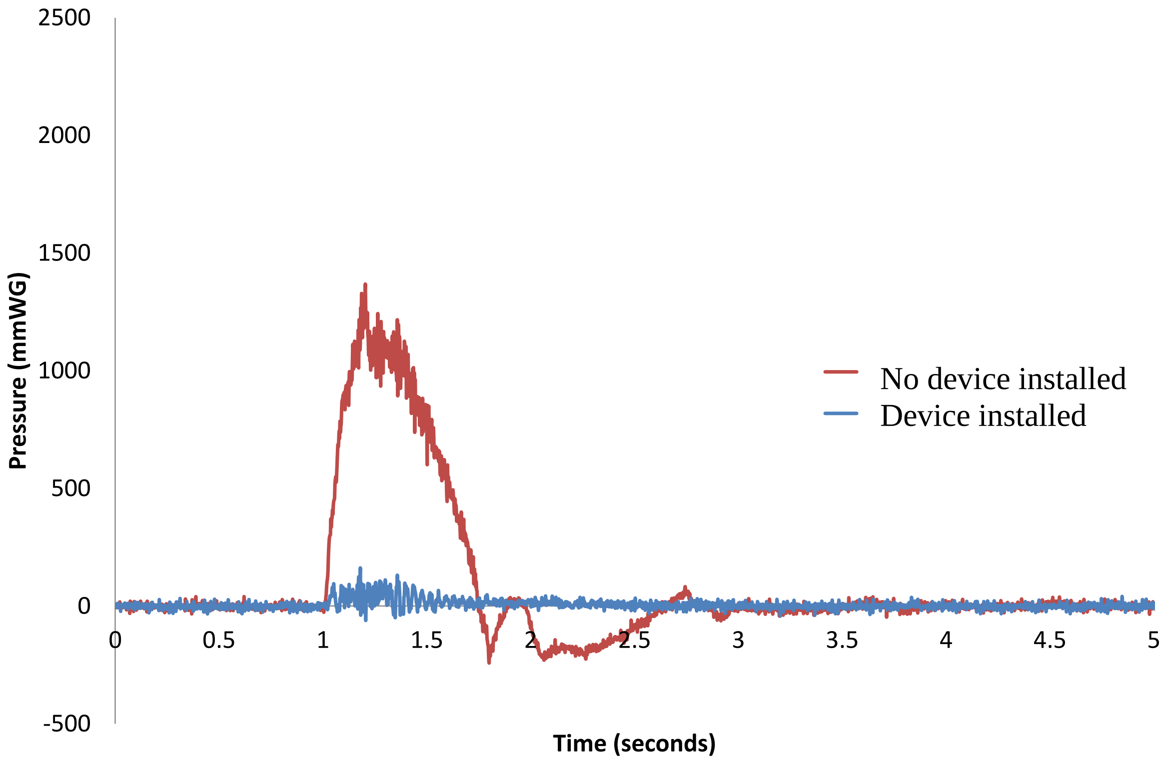

Figure 21: Comparison of the measured pressure response from the test rig with a toilet fitted 15m from pressure transducer T1 with and without the device fitted.

(a) (b) (c)

Figure 22: The effect of large pressure surge on a WC situated 3 floors from base of stack with no alleviation. (a) the pressure wave arrives at the WC and blows out the water seal; (b) the water seal is thrown out beyond the WC; (c) the water seal is completely removed from the WC.

Conclusions

This research sought to develop a technique for the attenuation of large magnitude pressure transients which have been experienced in tall buildings. It has also been shown, through the literature, that system designed using existing codes and standards will not be able to cope with large pressure transients. The consequences of breaches in the seal afforded by water trap seals are considerably more serious than the ingress of bad odours, indeed the spread of disease is a specific danger.

The theory associated with the development of an appropriate technique for dealing with large air pressure transients has been proven. The application of transient propagation theory, though the use of a computer modelling via AIRNET augmented by large scale high pressure/ volume tests in a full-scale test rig have all proven successful.

The technique described expands the possibilities for pressure alleviation in tall buildings with high pressure transient issues

This research set out to prove that an in-line device is effective at attenuating the type of pressure surge that can be experienced in tall buildings; characterised by very high pressures (in excess of 1 m wg) and containing a large volume of air. Both these issues are effectively dealt with by the prototype device which can reduce air pressure transients by up to 90% and dissipate a volume of 135 litres of air safely.

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