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2011

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PENGANTAR

Kemajuan suatu bangsa atau negara tidak terlepas dari tingkat penguasaan teknologi bangsa tersebut. Teknologi berperan penting dalam meningkatkan kemampuan atau kemakmuran suatu negara. Dengan teknologi manusia dapat memberikan nilai tambah terhadap sumber daya alam yang ada menjadi produk-produk yang bermanfaat bagi kepentingan masyarakat. Namun, di sisi lain kemajuan teknologi ini juga kadanng membawa kadampak yang tidak menguntungkan terutama pada alam.

Ekploitasi sumber alam yang berlebihan, pembuangan sisa-sisa aktifitas industri, serta penggunaan energi yang boros, memberikan dampak negatif pada keseimbangan alam. Pemanasan global dan perubahan cuaca yang sangat ekstrim telah dirasakan oleh seluruh penduduk di dunia. Kesulitan sumber air bersih pun juga telah dirasakan oleh masyarakat yang tinggal di kota-kota besar ataupun di pedesaan. Di sisi lain, banjir justru menjadi sebuah bencana bagi beberapa kota dimana pada dasarnya, hal itu dipicu oleh tata kelola yang tidak seimbang dengan alam.

Bertepatan dengan Hari Pendidikan Tinggi Teknik ke-65 Fakultas Teknik Universitas Gadjah Mada, Badan Pengelola Penelitian Fakultas Teknik sebagai panitia mengundang para akademisi, peneliti, maupun praktisi lingkungan untuk mepresentasikan gagasan ilmiah, karya ilmiah, dan hasil penelitian melalui Seminar Teknik 2011 yang mengambil tema: Towards Sustainable Engineering.

Dengan tema tersebut, solusi untuk melindungi kelestarian lingkungan dan sumber daya alam diterapkan dapat menjadi bagian dalam pengembangan teknologi di masa depan. Oleh karena itu, seluruh masyarakat seharusnya bersama-sama ikut berpastisipasi dalam pengembangan teknologi yang ramah lingkungan supaya bermanfaat bagi generasi selanjutnya.

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DAFTAR ISI

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C. KLASTER TEKNIK KIMIA, MESIN DAN INDUSTRI

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Seepage and stability analysis of earth dam due to the rising of upstream water level

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Abstract

A physical model of earth dam is constructed in a drainage and seepage tank in order to analyze the seepage and stability due to piping considering the rising of upstream water level. The dam model was made of Mt. Merapi sand deposit, with the upstream slope inclination of 1:1; 1:1.5 and 1:2. From the experiment, seepage discharge and permeability coefficient of the dam body and the relationship between the rising rate of upstream water level and slope stability can be analyzed. The result showed that the higher water rising rate, the smaller value of safety factor so that the dam is more prone to landslide. The smallest value of safety factor (SF) against landslide occurred in the steepest slope of 1:1, with the initial SF of 1.13 (before the rising) reduced to below 1.00 (after the rising). Accordingly, the highest critical rate of water level increment that triggers landslide occurred in the model with slope inclination of 1:1.5 at 0.545 mm/s. As the result of piping analysis, the smallest Weighted Creep Ratio against piping (WCR) of 1.86 occurs in the upstream slope with inclination of 1:2. In the dam management, continuous monitoring should be carried out to prevent the reduction of embankment stability that may exceed its critical value due to rapid rising of reservoir water level.

Keywords: rising rate of water level, dam failure, safety factor due to piping, stability against landslide.

1. Introduction

A dam, besides having a great benefit, has a risk to community's life and environment, and thus, needs a special treatment starting from the design, construction, and management phase. A failure in an earth dam is often started from failure signs in the upstream or downstream slope. A failure of an embankment body can also be caused by subsoil damage due to piping erosion. The erosion is often started with the cracks on the downstream embankment slope, followed with deformation of the embankment body and finally the embankment collapse. The other signs of failure are when the seepage emerges at the embankment toe and the water flows and erodes the slope, threaten the embankment stability [1].

An embankment failure can be avoided if the upstream and downstream slope is stable and safe at any condition, whether when the dam is full, empty, or when sudden rising or drawdown of water level happens. At the highest reservoir water elevation, the pore pressure is very high; the uplift pressure acting on the dam core, and thus, reducing its effective weight and weakening the dam stability. When the water level drops drastically, the pore water pressure will slowly dissipate. Likewise, in wet condition, the total weight increases since there is no uplift water pressure [2, 3].

The mechanism of collapsed earth dam is related to water fluctuation and its interaction with soil materials composing the dam that form a seepage line in the dam body [4, 5]. A reservoir-induced landslide modeling has been performed on one side of dam slope. The result showed that the drawdown rate and slope inclination highly affect the stability of the dam slope [6].

Based on the above explanation, the effect of the rising of upstream water level to seepage, stability analysis due to piping, and critical rising rate of water level to earth dam overall stability should be analyzed. By conducting the experiment on a physical model of earth dam, the dam stability

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will be evaluated by considering the rising rate of water level, slope inclination, and material composing the dam body.

2. Research methodology

2.1. Material and apparatus

The earth fill dam as a model in this research used Mt. Merapi sand deposit that passed sieve no. 10 (2 mm) and was retained in sieve no. 200 (0.075 mm). All model variation were designed with density (γ) of 1.7 gr/cm^3 and water content (w) of about 12%.

The main apparatus used in the research is Drainage and Seepage Tank as shown in Figure 1. The earth dam was modeled in the apparatus with upstream slope inclination variation of 1:1; 1:1.5; and 1:2.

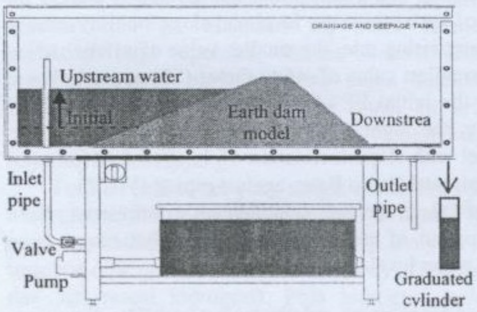

Figure 1. Rapid rising of upstream water level experiment on a drainage and seepage tank.

The modified valve was placed on the pump and inlet pipe of the tank. This apparatus is used to measure the rising rate of water level at the upstream of the model. In order to measure the deformation occurring in the dam body, a dial gauge placed on the dam crest and two dial gauges placed on the downstream slope, as shown in Figure 2.

2.2. Stage of experiment

The structural modeling of earth dam was made in such a way in drainage and seepage tank so that the landslide process can be well observed. The height, crest width and downstream slope inclination of the model were made to be constant. However, upstream slope inclination was varied, i.e.: 1:1; 1:1.5; and 1:2. The earth dam model with the inclination of 1:1 is shown in Figure 2.

The water used in this experiment was colored to make the observation easier. Height parameter and various rising rate of upstream water level were determined and controlled through a valve. The phases of the experiment are described as follows.

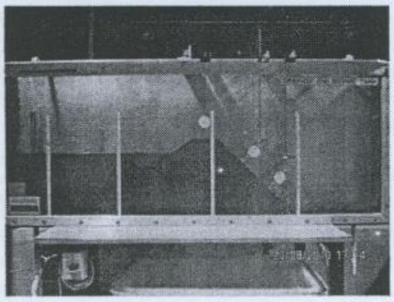

Figure 2. Earth dam model with upstream and downstream slope inclination of 1:1.

2.2.1 Seepage experiment

The experiment was started by flowing water to the upstream of the model through an inlet pipe which the discharge rate was controlled by using a valve. The rising of water level during the experiment was observed and recorded to find out the time needed to reach stable level. Water flowing out through the outlet pipe was measured with a graduated cylinder, which is determined as the value of the occurring seepage. This phase was conducted every 15 minutes.

The seepage experiment was halted when the water reached stable level and the seepage discharge measured in the graduated cylinder reached a constant value. Further, with the same method, the experiment was continued with different variations of valve opening until the water reached the elevation of 250 mm or the dam model had not shown any landslide indication.

Models with slope inclination of 1:2; 1:1.5; and 1:1 were given symbols *A*, *B* and *C*. Models with valve opening of 1,2 and 3 were given symbols *I*, *II* and *III*. The implementation of seepage experiment was given symbol *P*. Therefore, seepage experiment with upstream slope inclination of 1:2 and valve opening of 1 was given symbol *PAI*.

2.2.2 water level fluctuation experiment

The rising rate of water level occurring during the experiment was observed, and recorded to find out the time needed to reach its maximum level of 250 mm. At the same time, an observation was conducted on the landslide occurrence. Models with the slope inclination of 1:2; 1:1.5; and 1:1 were given symbols *A*, *B* and *C*. Models with valve opening of 1, 2, 3, were given symbol *1*, *2*, *3*, and so on. The implementation of water level rising experiment was given symbol *R*. Hence, the water level rising experiment model with upstream slope inclination of 1:2 and valve opening of 1 was given symbol *RA1*.

From the result of the experiment, the seepage discharge and permeability coefficient of the dam body, and the relationship between water rising in the upstream and slope stability could be analyzed. The analysis of the slope stability was conducted by using a limit equilibrium method of Slope/W, by assuming the model characteristic as conducted in the dam modeling experiment in the laboratory.

3. Results and Discussions

3.1. *Seepage analysis*

In designing a dam, the stability level against landslide, slope erosion, and water loss due to seepage through the dam body should be considered. Analysis on the seepage discharge occurring in the model was based on the water volume measured by a graduated cylinder at its outlet during a certain period. This signifies that water discharge coming into the model is similar to discharge coming out of the model.

Based on the result of the research, it can be observed that the seepage discharge will increase as the upstream water level rises. The water flowing in to the dam body will pass the sand layer in the body and the hydrodynamic pressure acting on the sand particle depending on the flow direction.

The seepage pressure will increase as the hydraulic gradient increases. The hydraulic gradient was affected by the difference of water level in the upstream and downstream. As a result, water level rising in the upstream of the model will increase the value of hydraulic gradient, causing an increase in the seepage discharge. Figure 3 shows the relationship between seepage discharge and upstream water level.

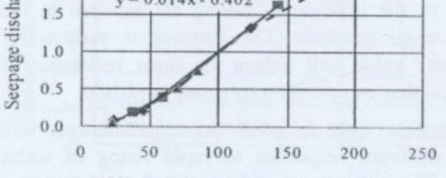

Figure 3. Relationship between seepage discharge and upstream water level.

The seepage discharge occurring in every variation of slope inclination made a linear relation. This explains that the seepage discharge in the dam model is not affected by the upstream slope inclination and is linear to the upstream water level. In a seepage experiment for slope inclination of 1:2, simulation until valve opening of 4 (PAIV) and 5 (PAV) was conducted. In the opening of 4, it can be seen that the downstream slope experienced a landslide of 122 mm height. The landslide height increased to 200 mm due to the rising of upstream water level of 282 mm (opening 5), as shown in Figure 4 and 5. Consequently, the graph for slope inclination of 1:2 in Figure 3 has a different trend from the others.

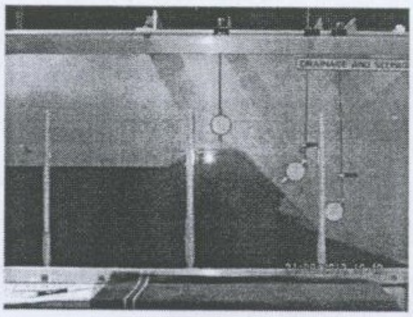

Figure 4. Dam failure of a model with upstream inclination of 1:2 and valve opening 5 (PAV).

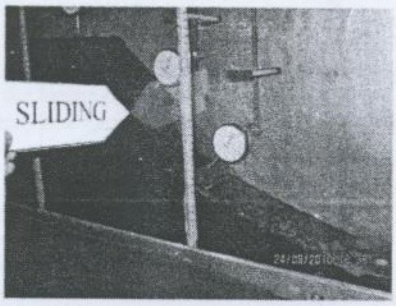

Figure 5. Toe sliding at the downstream slope of the model PAV.

Based on the result shown in Figure 3, the permeability coefficient will decline as water level in the upstream of model rises. The decline occurred in all models. For all types of upstream slope observed, the graph will show similar trend, i.e. the permeability coefficient value will decline as water level in the upstream rises. Therefore, it can be concluded that the change of permeability coefficient is not significantly influenced by the inclination of upstream slope in the model, but by soil type, grain size, particle shape, mass density, and the pore geometrical shape.

3.2. Dam Stability against Piping

If the seepage pressure in the soil is equivalent to critical hydraulic gradient, the fine particle of sand will be transported, causing piping in the earth dam. This may disturb the dam stability, which eventually may cause landslide. A parameter commonly used to measure whether an embankment construction is safe from the risk of piping is stated in a Weighted Creep Ratio (WCR). A construction is deemed to be safe when it has a higher value above a minimum WCR. Materials used in the model are coarse sand, which has WCR minimum value of 5.

Figure 6 shows the value of WCR against the risk of piping for all dam models. Based on the figure, it can be concluded that the higher water level in the upstream of the model, the smaller the WCR is. This signifies that the model has higher risk of landslide due to piping.

The slope inclination also affects the value of WCR. By reducing the inclination, flow path of the seepage flow (L_w) will be longer. Therefore, with the same upstream water level, a slope with gentler inclination will have higher WCR compared to slope with steeper inclination.

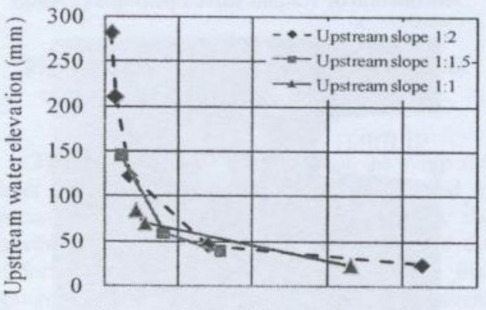

Figure 6 Relationship between the upstream water level and Weighted Creep Ratio (WCR).

In Table 1, the value of WCR for every model is shown. Based on the table, a model with WCR below 5 will tend to collapse. For PAIV model with upstream water level of 210 mm, the downstream slope had experienced landslide and had WCR of 3.05.

Table 1 WCR and safety factor against piping

Model	Upstream (H_u) (mm)	Down-stream (H_d) (mm)	L_w (mm)	dH (mm)	*WCR*	Landslide Height (mm)	Landslide Type
PAI	24	13	939	11	85.37	-	-
PAII	45	13	898	32	28.05	-	-
PAIII	123	13	749	110	6.81	-	-
PAIV	210	13	600	197	3.05	122	sliding
PAV	282	13	501	269	1.86	200	sliding
PBI	38	13	780	25	31.22	-	-
PBII	59	13	750	46	16.3	-	-
PBIII	144	13	635	131	4.84	30	sliding
PCI	23	13	664	10	66.41	-	-
PCII	70	13	620	57	10.87	-	-
PCIII	85	13	606	72	8.42	-	-

For PAV model, landslide occurred when the upstream water level was at 282 mm and WCR was at 1.86. Similar to PAIV and PAV model, landslide in PBIII model occurred when water level reached 144 mm and the WCR was 4.84. Those three models experienced landslide as their WCR values were lower than the minimum critical value. Other models did not experience any landslide and based on the analysis result, the WCR values of the other models were bigger than the minimum WCR for sand.

3.3. Dam Response to Rapid Rising of Upstream Water Level

The rapid rising of water level was performed with a centrifugal pump that flowed water to the seepage and drainage tank. Water was constantly flowed with the same valve opening until it reached the determined level of 250 mm. Rapid rising of the water level on the upstream gave a significant impact to the model slope as a landslide occurred in the downstream slope. The landslide was started on the slope toe and it grew as the water level in the upstream rose. This is due to the rising of water level in the upstream, causing an increase in the pore water pressure. The increase in pore water pressure value will reduce the shear resistance of the soil that eventually may cause landslide.

Models with different slope inclinations will give different responses to rapid rising of water level. The response was shown by the safety factor (SF) against slope failure. Model RA4 had slope inclination of 1:2 with valve opening 4. At the water level of 20 mm, that is the level before rapid water rising occurred, model RA4 had a safety factor of 1.51 at the downstream slope. When a rapid rising of water level in the upstream occurred, the safety factor of model RA4 was reduced to 0.971 at the water level of 200 mm. Based on the simulation result, model RA4 experienced landslide with landslide height of 80 mm in the downstream slope. The decline in the safety factor value also occurred in the models with slope inclination of 1:1.5 and 1:1. Models with different inclination will have different state of safety factor although the water level is the same. The smaller the inclination, the higher the stability level compared to the other models.

The landslide in this condition was started with sand gradient movement in the upstream as the water level in the upstream rose. The sand gradients were then fallen and gathered at the toe of the upstream. On the toe of the downstream, continuous erosion occurred, causing a landslide which started from the toe of the downstream. The landslide increased as the water level in the upstream rose due to an increase of seepage pressure in the dam body. The landslide of this process was in the form of nearly a circular sliding surface.

As an illustration of the relationship between sliding rate, time of sliding occurrence and safety factor can be seen in Figure 7. The figure shows that rapid rising of water level will affect the landslide level of dam level. The higher rising rate of water level, the lower upstream critical level that may cause landslide on the downstream toe of the model is. RA4 and RC4 Model had the same inlet valve opening with different inclination. The RA4 Model with gentler inclination than RC4 model had landslide critical rate of 0,072 mm/s and landslide height of 80 mm. In RC4 model, the landslide occurred is bigger and the critical rate is also slightly higher compared to RA4 model.

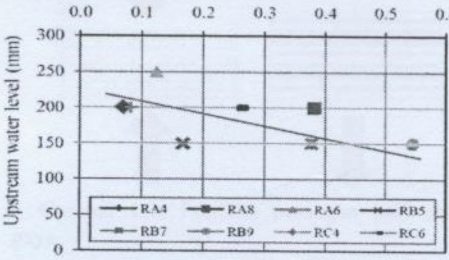

Figure 7. Relationship between the rate of sliding and sliding height.

The critical rate of RC4 model is 0.083 mm/s and the landslide height is 85 mm. The same thing also happens with RA6 and RC6 model. RC6 Model had bigger landslide height than RA6 model since the model had steeper inclination with higher critical rate (Figure 7).

RA4 model has landslide critical rate of 0.070 mm/s. The landslide occurred at RA4 model with landslide height of 80 mm when the upstream water level was 200 mm. RA8 Model had the same inclination with RA4 Model. However, the relation between upstream water level when a landslide occurs and landslide rate is not strongly correlated. RA8 Model had a higher landslide rate than RA4 at 0.382 mm/s. At the same upstream water level, RA8 model was supposed to have bigger landslide height than RA4 model. However, in the experiment, RA8 model had a smaller landslide height of 65 mm. This may happen since one model and another have different density level.

4. Conclusions

The earth dam model experiment which was conducted to find out the effect of rapid rising of water level is one of the ways to learn about earth dam failure from hydro-geotechnical aspect. Several conclusions obtained from the seepage and earth dam model stability analysis are discussed as follows. The seepage discharge in the dam body increases as the upstream water level rises, and the biggest increase happened in the PAIV model at 2.222 ml/s with the water level of 210 mm. The permeability coefficient of the dam body declines as the upstream water level rose due to varied density and the biggest was in PAI model at 0.1284 cm/s.

In the seepage experiment, the biggest landslide in the downstream occurred in PAV model at 200 mm with water level of 282 mm. The lowest safety factor against piping (WCR) occurred in PAV model at 1.86 with landslide height of 200 mm. The highest critical rate that triggered landslide during rapid rising of water level occurred in RB9 model at 0.5455 mm/s whereas the lowest safety factor (SF) against landslide due to rapid rising of water level occurred in RC6 model at 1.127 (before the rising) and below 1.00 (after the rising).

The results of the analysis in the form of seepage, permeability, and slope stability principles were given to study their effects to the consistency and integrity of a dam due to rapid rising of water level. It is expected that it can be a consideration in operating a dam optimally. The current earth dam construction design should consider the Standard Operational Procedure for spillway and embankment structure of the dams to prevent landslide due to rapid rising of water level.

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SMOKE RELEASE MANAGEMENT IN A WAREHOUSE

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Abstract

This paper describes smoke releasing calculation for a warehouse in a pharmaceutical industry. Fire protection for the warehouse consists of an automatic sprinkler and an internal hydrant box. Moreover, smoke release windows also should be provided for releasing the smoke to a location which is remote from the fire. A vent system shall be designed to slow, stop, or reverse the descent of a smoke layer produced by fire in a building, by exhausting the smoke to the exterior. Also, it shall be designed in accordance with the standard by calculating the vent area required to achieve a mass rate of flow through the vents that equal the mass rate of smoke production. Moreover, it shall limit the descent of the smoke layer to the design elevation of the smoke layer boundary. Air inlets shall be provided for supplying makeup air for vent systems. Air inlets consisting of louvers, doors, dampers, windows, shutters, or other approved openings shall be designed and constructed to provide passage of outdoor air into the building. The mass flows of smoke, fresh air inlet and window's area required for releasing the smoke will be estimated with an assumption of the warehouse as a building that has a large space where the fire size is steady. The smoke releasing calculation has been done referred to ASHRAE 1999 and NFPA 2001 as well as SNI 03-657-2001 standard and the minimum cross section of the window's area to vent the smoke is found 2.64 m^2, approximately. The calculation result based on the standard has been compared to the rule of thumb method, it gives 7.15 m^2.

Keyword: Fire protections, smoke release, vent system.

1. Background of Problem

Figure 1 shows a warehouse schematically. It has 65 m, 22.1 m, and 11.83 m of length, width, and height, respectively. Some windows will be provided on the wall for both releasing smoke and fresh air intake when the building in fire. Those will be located at 9.65 m from floor for smoke release window and at 1.74 m from floor for fresh air intake window. The property inside the building is assumed as a compartment that has fire size 25000 kW as a typical rate of heat release per unit floor area. The approach established for estimating both the mass flow and windows area is by treating the building as a building that has a large space where the fire size is steady.

In warehouse fires, smoke flows to locations remote from the fire. A smoke detector located inside will sense the smoke in the building and will send signal to a fire alarm system so that the window actuator operated by pneumatic will open the windows and then the smoke will be released through the smoke release windows. In addition to, an automatic head sprinkler will active when the temperature rating is achieved. Hence, both the smoke release and fresh air intake windows have a function as a vent and an inlet system.

2. Vent System

A vent system shall be designed to slow, stop, or reverse the descent of a smoke layer produced by fire in a building, by exhausting the smoke to the exterior. Also, it shall be designed in accordance with the standard by calculating the vent area required to achieve a mass rate of flow through the vents that equal the mass rate of smoke production. Moreover, it shall limit the descent of the smoke layer to the design elevation of the smoke layer boundary.

Alternative vent system designs shall be permitted to be developed in accordance with this standard by calculating the vent area required to achieve a mass rate of flow through the vents that are less than the mass rate of smoke production, such that the descent of the smoke layer is slowed to meet the design objectives.

Normally, closed vents shall be designed to open automatically in a fire to meet design objectives or to comply with performance objectives or requirements. Vents, other than thermoplastic drop-out vents, shall be designed to fail in the open position such that failure of a vent-operating component results in an open vent. Vents designed for remote operation shall utilize approved fusible links and shall also be capable of actuation by an electric power source, heat-responsive device, or other approved means. Vents are designed to be activated by smoke detection, sprinkler water flow, or other means of detection.

3. Inlet System

Air inlets shall be provided for supplying makeup air for vent systems. Air inlets consisting of louvers, doors, dampers, windows, shutters, or other approved openings shall be designed and constructed to provide passage of outdoor air into the building. Air inlets shall be installed in external walls of the building below the height of the design level of the smoke layer boundary and shall be clearly identified or marked as air inlets.

To satisfy the vent system requirements, air inlets shall consist of one of the following:

- A single unit (air inlet) in which the entire unit (air inlet) opens fully with the activation of a single detector
- Multiple units (air inlets) in rows or arrays (ganged air inlets) in which the units (air inlets) open simultaneously with the activation of a single heat detector, a fusible link, a smoke detector, a sprinkler water flow switch, or other means of detection to satisfy the vent system requirements

Air inlets and their supporting structures and means of actuation shall be designed such that they can be inspected visually after installation. Air inlets shall be either constantly open or automatically placed in the open position after a fire is detected. Air inlets shall be designed to open in a fire to meet design objectives or to comply with performance objectives or requirements. Air inlets shall be designed to fail in the open position such that failure of an air inlet–operating component results in an open air inlet. Air inlets shall be opened using an approved means as the opening force. Air inlet opening mechanisms shall not be prevented from opening the air inlet by debris, or internal projections.

Operating mechanisms for air inlets shall be jam-proof, corrosion-resistant, dust resistant, and resistant to pressure differences arising from applicable positive or negative loading resulting from environmental conditions, process operations, overhead doors, or traffic vibrations.

Air inlets designed for remote operation shall be activated by approved devices and shall be capable of actuation by an electrical power source, heat-responsive device, or other approved means.

4. Smoke management in large space (atrium)

The term atrium is used in a generic sense to mean any of these large spaces. Most atrium smoke management systems are designed to prevent exposure of occupants to smoke during evacuation. The following are approaches that can be used to manage smoke in atrium:

- **Smoke filling**. This approach consists of allowing smoke to fill the atrium space while occupants evacuate the atrium. It applies only to spaces where the smoke filling time is sufficient for both decision making and evacuation.
- **Unsteady clear height with upper layer exhaust.** This approach consists of exhausting smoke from the top of the atrium at a rate such that occupants have sufficient time for decision making and evacuation.
- **Steady clear height with upper layer exhaust.** This approach consists of exhausting smoke from the top of the atrium in order to achieve a steady clear height for a steady fire.

The design fire has a major impact on the atrium smoke management system. Fire size is expressed in terms of rate of heat release. Fire growth is the rate of change of the heat release rate and is sometimes expressed as a growth constant that identifies the time required for the fire to attain a particular rate of heat release. Design may be based on either steady fires or unsteady fires.

It is nature of fires to be unsteady, but the steady fire is a very useful idealization. Steady fires have a constant heat release rate. In many applications, use of a steady design fire leads to straight forward and conservative design.

Unsteady fires are often characterized by the following equation:

$$q = 1055\left(\frac{t}{t_q}\right)^2 \qquad (1)$$

Type growth times are listed in Table 1 below.

Table 1 Typical Fire Growth Times

Unsteady fires	**Growth time t_g, s**
Slow	600
Medium	300
Fast	150
Ultra fast	75

Table 2 Steady Design Fire Size

	kW
Minimum fire for fuel-redistricted atrium	2000
Minimum fire for atrium with combustibles	5000
Large fires	25000

The following experimental correlation of the accumulation of smoke in a space due to a steady fire is the steady filling equation:

$$\frac{z}{H} = 1.11 - 0.28 \ln \left[\frac{t_q^{(1/3)} H^{4/3}}{A/H^2} \right] \quad (2)$$

The above equation is appropriate for,

$$0.2 \le \frac{z}{H} < 1.0$$

$$0.9 \le \frac{A}{H^2} < 14$$

Figure 1 illustrates smoke exhaust from the hot smoke layer at the top of an atrium to maintain a steady clear height. The smoke flow into the upper layer from the fire plume depends on the heat release rate of the fire, clear height, fuel type, and fuel orientation. The following is generalized plume approximation that does not take into account the specifics of the material being burned.

$$\dot{m} = 0.071 q_c^{1/3} z^{5/3} + 0.0018 q_c \quad (3)$$

The clears height z is the distance from the top of the fuel to the interface between the “clear” space and the smoke layer. Because a smoke management system generally must protect against a fire at any location, it is suggested that the top of the fuel be considered at the floor level.

Volumetric flow is expressed as,

$$Q = \dot{m}/\rho \quad (4)$$

The cross section area of windows can be calculated by the following equation:

$$A = Q/V \quad (5)$$

Rule of thumb method

In practice, the following equation is used generally to calculate the cross section area for smoke release windows:

A_v = 0.50 % x foot print area (6)

A_i = 0.75 % x foot print area (7)

5. Smoke release and fresh air intake area

The minimum cross section area for smoke release can be estimated by a combination of equations (3), (4) and (5). With idealization fire size steady (25000 kW) and z = 0.2, the minimum cross section of smoke release windows can be obtain.

The convective portion q_c of the heat release rate in equation (3) can be expressed as

$$q_c = 0.7\ q$$

Where, q = 25000 kW, thus the convective heat release rate is 17500 kW.

So, the mass flow rate of plume is

$$\dot{m} = 0.071 x (17500)^{1/3} x (0.2)^{5/3} + 0.0018 x (17500)$$

$$\dot{m} = 0.126 + 31.5$$

$$\dot{m} = 31.63 kg/s$$

From equation (4), the volumetric flow of exhaust gas, Q = 26.4 m^3/s. Generally, Air flow velocity through the windows has range 2.5 – 10 m/s. Thus, the minimum area of cross section windows is

$$A = \frac{26.4 m^3/s}{10 m/s} = 2.64 m^2$$

Rule of thumb method

From equation (6) and (7), the cross section area for smoke release windows A_v and fresh air intake A_i are

A_v = 0.50 % x foot print area
= 0.5 % x 1430 m^2
= 7.15 m^2

A_i = 0.75 % x foot print area
= 0.75 % x 1430 m^2
= 10.73 m^2

Thus, by the rule of thumb method, the cross section area is 7.15 m^2 and 10.73 m^2 for smoke release and air intake window, respectively.

6. Summary

From the above explanation about smoke management and calculation can be summarized as follows:

a. Smoke release and fresh air intake windows has function as vent and inlet system to flows smoke to location remote the fire.
b. The minimum cross section of vent system is 2.64 m^2. Alternate calculation by the rule of thumb method gives 7.15 m^2 and 10.73 m^2 for vent and inlet area, respectively.

7. References

[1] ASHRAE 1999, HVAC Application, Chapter 15, Fire and Smoke Management
[2] NFPA 92A, Recommended Practice for Smoke Control System 2000 edition
[3] NFPA 92B, Guide for Smoke Management 2000 edition
[4] NFPA 204, Standard for Smoke and Heat Venting 2002 edition
[5] SNI 03-657-2001

8. Abbreviation and Unit

m = Mass flow, kg/s
z = Clear height from floor, m
h = height of building, m
H = Windows elevation from floor, m
Q = Heat release, kW
qc = Convective heat release, kW
Q” = Heat release per area floor, kW/m^2
V = Flow velocity, m/s
Av = Window’s area, m^2
A = Floor area, m^2
ρ = density of plume, kg/m^3
t = time, s
t_g = growth time, s

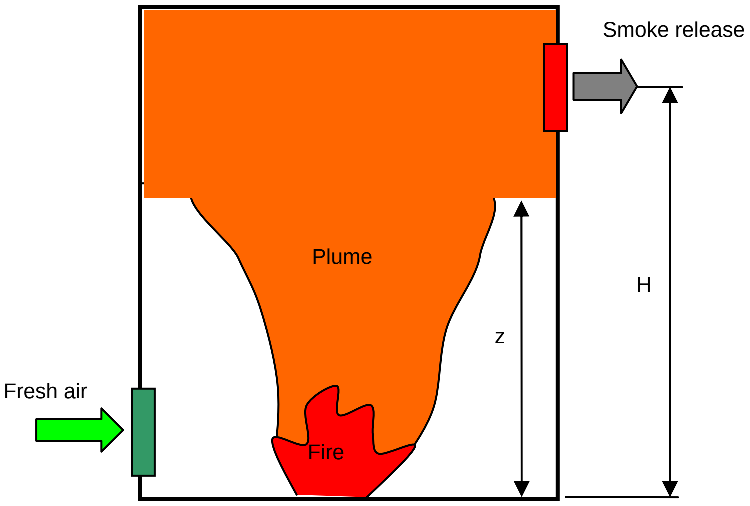

Figure 1 Smoke exhaust in a Warehouse schematically