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REVIEW ARTICLE

A Review Study of Crowd Behavior and Movement

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Abstract. The efficient and safe operation of heavily crowded facilities used in special circumstances by unfamiliar users (e.g. Hajj) is a major concern to those responsible for the design and control of such public places and events. This paper presents a review of studies directed at the characterization of crowd behavior and movement. It appears that the theory of pedestrian traffic flow, for orderly movement under normal conditions, has been sufficiently developed to reflect the actual behavior of foot traffic flows in such context, and thus can be adopted for design and control purposes. On the other hand, the review reveals that virtually no scientific basis appears to be available in the literature to design and analyze strategies for the management of very large crowds associated with special events. The review of relevant Hajj studies shows that very limited research has been directed at crowd behavior and movement during the Hajj. Modelling capabilities are needed there to help better understand this unique phenomena, and thus prevent the occurrence of more crowding tragedies. The challenge for any future research, then, is to develop useful and accurate means for predicting normal crowd behavior, and for enabling facility managers and designers to evaluate various scenarios before costly mistakes are made.

Introduction

Crowding occurs normally in many human activities. High volumes of pedestrians are processed daily through transportation terminals, high rise buildings, stadia, and various types of public facilities. Efficient crowd management and control is a determinant of the quality of the human experience in these environmental settings, and a critical safety consideration.

Crowd disasters, in which people are seriously injured or even killed due to crushing or trampling, are not restricted to emergencies such as fires, to conditions of crowd violence, or to the exuberance of some members of a crowd. Such incidents can occur, and have occurred, at sports events, religious gatherings and rock music concerts. A review of such incidents can be found in [1]. Serious injury and even death can occur during entry, occupancy and evacuation of a public event facility.

A remarkable example of pedestrian overcrowding is that of the Hajj, the Muslims' pilgrimage to Makkah, Saudi Arabia, which provides the motivating context for this review.

Crowding disasters have been viewed as a type of pedestrian traffic process in which certain critical performance limits have been exceeded. Fruin defines it as the rapid coming together of a group of persons in a constricted space with sufficient mass and force to cause human injury or death [1].

An understanding of the system dynamics contributing to a crowd disaster is a necessary prerequisite to developing appropriate crowd management and control techniques, as well as design standards for crowd facilities.

In general, observed variations in crowd behavior (B) may be attributed to variation in three factors: crowd characteristics (C), facility design and layout (F), and **management practices (M)** [2]. That is:

$$B = f(C,F,M) \tag{1}$$

The term "crowd behavior" (B) is a complex variable consisting of several interrelated phenomena. These include, but are not limited to, the physical characteristics of crowds and their movement (e.g. measures of flow rates through sidewalks and concentration of people in a space), normal crowd dynamics (i.e. the normal process by which crowds form, change, and dissolve), and triggering mechanisms that transform normal crowds into potentially hazardous mobs. Crowd characteristics (C) may, for any given event, be defined in terms of demographic data, total quantities of patrons, degrees of aggregation within an overall crowd, and such affective factors as the "mood" of the crowd. Facility design and layout (F) refers to the facility's overall configuration, layout of circulation elements, links with transportation facilities and parking, and capacities of means of ingress and egress. Management practices (M) include decisions about staffing, communications, security, admissions, and furnishings, which may vary form one event to another.

Accordingly, if a facility manager or designer possessed an equation (or a model) which accurately specified the relationship among these factors, then the professional could predict, reasonably closely, crowd behavior at a particular future event on the basis of anticipated crowd characteristics, facility design conditions, and management decisions.

Surprisingly little scientific work has been directed at the characterization of crowd behavior, leaving considerable gaps in the knowledge base and methodological capabilities pertinent to this problem.

The available literature related to crowd behavior and movement is reviewed in this paper. The limited body of these studies can be classified, for convenience, into two broad categories: 1) those that deal with steady-state pedestrian flows under normal conditions, and 2) those that address crowding conditions.

In the first section of the paper, a general review of previous research on pedestrian movement is presented, followed by a more detailed discussion of studies that address pedestrian traffic flow theory, characteristics and design standards, for steady-state flows under normal conditions. Studies that address crowding conditions, which correspond to the higher end of the concentration spectrum, and generally involve multidirectional flow patterns with strong interactions, are reviewed next. These studies are classified into two distinct categories: socio-psychological studies that describe the qualitative aspects of crowd behavior, and the relevant quantitative modeling studies. A review of studies directed at crowd behavior and movement during the Hajj is then presented. The paper is concluded by a discussion of key points revealed by the review.

Pedestrian Studies

2.1 General

Two main trends can be identified in the research that has been conducted on pedestrian movement.[1] The first and older of the two has been concerned with pedestrian accident research. This research has typically involved an analysis of accident reports in an attempt to identify accident-prone pedestrians, behavior, and situations [e.g. 6,7,8]. More recent accident research has examined in detail the decisions and behavior involved in crossing a street in the face of on-coming traffic [e.g. 9,10,11,12].

The second line of research is somewhat more comprehensive as it is concerned with pedestrian circulation as a system. Two broad sub-areas within this trend can be

1 For general bibliographies on pedestrian research, see [3,4,5].

distinguished: 1) research that examines the overall pedestrian system with regard to its patterns of movement and circulation [13], and 2) research on pedestrian traffic flow theory, characteristics and design standards.

For transportation and urban planning purposes, circulation patterns have been analyzed in order to determine the influential causal variables. These variables are usually land-use and population characteristics. Such analyses have been used as a basis for forecasting future circulation patterns [e.g. 14,15,16].

Design standards have been developed to serve as guides in evaluating the capacity of any particular component of the pedestrian system, such as a sidewalk or stairway. The standards include descriptions of pedestrian movement under different levels of crowding, and classifications of differences in walking behavior by age, sex, occupation, trip purposes, trip length, and other relevant variables [17]. Fruin has incorporated many of the standards that have been developed into a single reference [4], and substantially advanced the state of the art with his work on pedestrian queuing and level of service standards. A more detailed review of the research on pedestrian traffic flow theory, characteristics and design is presented in the following sub-section.

2.2. Pedestrian traffic flow studies

The Institute of Architecture of the Russian Academy of Arts (VAKH) appears to have been the first to study pedestrian traffic flow, in 1937 [18]. The principal scientific achievement of this study was establishing that the speed of pedestrian flow, u, is inversely proportional to the prevailing concentration of pedestrians, k, that is $u = f(1/k)$, though the specific quantitative results obtained were unreliable because of the relatively small number of actual observations, and other inadequacies discussed in [18].

The Central Scientific Research Institute of the Russian Fire Protection Service (VNIPO) conducted a study, between 1946 and 1948, to obtain reliable quantitative expressions characterizing pedestrian traffic flows. Average sizes of the horizontal projection of the human body (an ellipse) for different age groups, in both winter and summer clothing, were established, based on a large number of observations made in public buildings, such as theaters, and industrial, educational and transportation facilities. The study introduced the measurement of the concentration of pedestrian traffic as the sum of the horizontal projections of the individuals occupying a unit area, or the occupancy ratio. This work resulted in two major contributions. The first was to observationally verify that the pedestrian flow rate, q, equals the product of the stream's speed times its concentration, that is $q = u * k$, which is a well known relation in traffic flow theory. The second contribution was the introduction of the graphical approach of studying pedestrian traffic flow, in terms of time-space diagrams. Thus, the work of VNIPO has, indeed, advanced the understanding of the mechanics of pedestrian traffic flows and contributed to subsequent efforts aimed at developing a more comprehensive theory of pedestrian traffic flow [18].

Hankin and Wright [19] investigated the flow of passengers in London subways, and observationally established relations between speed, concentration and flow for unidirectional pedestrian flow. More recent studies of the relationships among these variables include those by Oeding [20] on mixed traffic (e.g., shoppers, commuters, sports spectators), Predtechenskii [21] on mixed mass[2] as the movement that is characterized by simultaneous displacement of a large number of people within a relatively limited area. Older [22] on shoppers, Navin and Wheeler [23] on students, and Fruin [4] on commuters. A synthesis of the above speed-concentration, flow-concentration, and flow-speed relations are shown in Figs. 1 a,b and c, respectively, which depict a family of curves abstracted from the measurements reported by the investigators cited previously and converted to common units. It should be noted that all of these studies were restricted to streamlined and orderly pedestrian movements under steady-state conditions.

While most of these studies have dealt with undirectional pedestrian flows, Older [22], Navin and Wheeler [21] and Fruin [4] have studied pedestrian flows in two opposing directions, in a sidewalk environment. These studies found that the two groups of pedestrians split into two distinct streams. Pedestrians traveling in the same direction tend to follow one another in 'files' which interweave with those from the opposite direction. Thus, the interaction between the two flows is reduced and limited to the interface line of the two streams [22].

A linear relation was specified between speed and concentration in all the reported studies, with the exception of those by Hankin and Wright [19] and Predtechenskii [21], [Fig. 1a], according to the following form:

$$u = u_f - (u_f/k_j)\, k \tag{2}$$

where u_f represents the theoretical speed attained by a traffic stream under conditions of completely free flow, with a practically unlimited amount of space per pedestrian, and k_j is the jam concentration, at which all movement in a traffic stream grinds to a halt and speed becomes zero.

[4]Predtechinskii and Milinsk; [18] defined mass movement

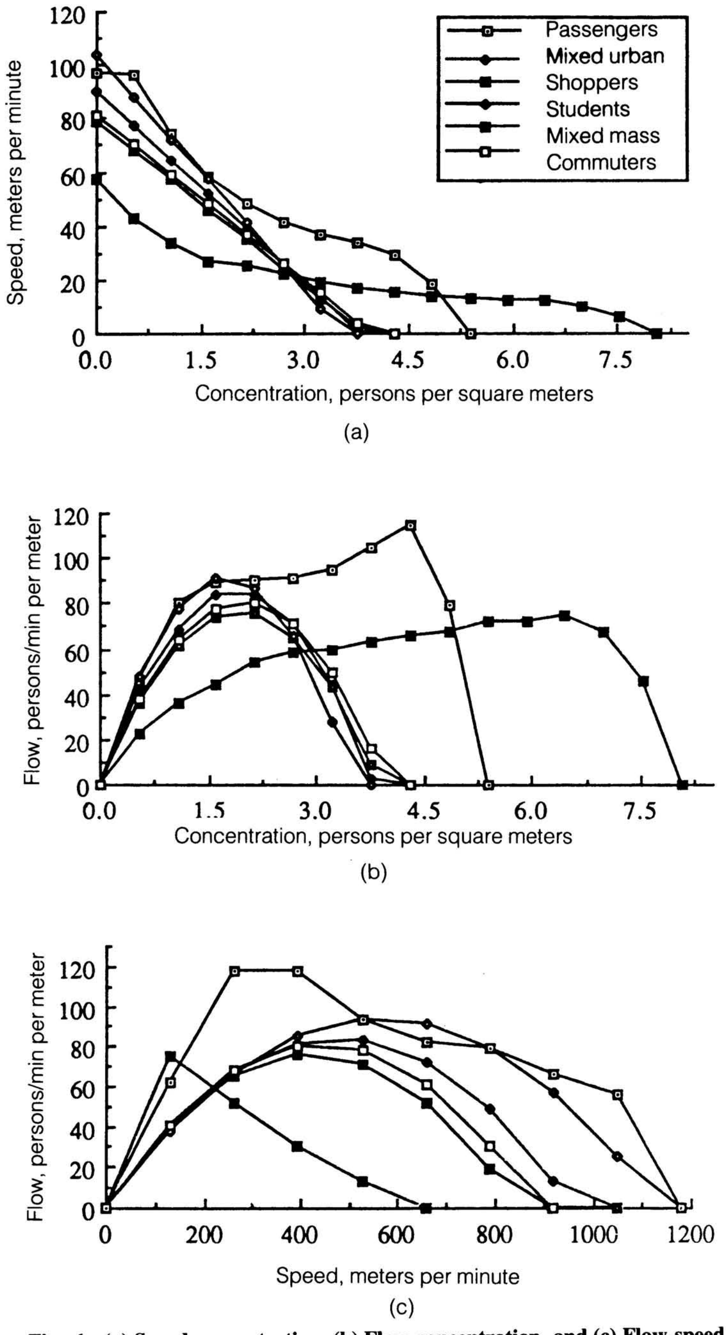

Fig. 1. (a) Speed-concentration, (b) Flow-concentration, and (c) Flow-speed relations for normal steady-state pedestrian flows.

The linearity of the speed-concentration relation has been questioned for both vehicular [24] and pedestrian flows [25]. Indeed, there is some tendency for observations to depart from a constant slope both in the high-and low-concentration ranges, for both vehicles and pedestrians. At very high concentrations, flow resists grinding to a complete halt and attempts to maintain some speed (i.e. shuffling) even with minimal allocation of space, while at very low concentrations, speeds may not expand proportionately to rising space allocations because of imposed or inherent speed limits [25]. However, a thorough statistical investigation of seven different hypotheses concerning the shape of the speed-concentration relationship for vehicular flow indicated that the differences among them are rather small [26]. Unfortunately, no such thorough testing appears to have been performed for pedestrian flows, although a study limited to one particular site [27] suggested that further study is likely to lead to the conclusion that a multi-regime (probably a 2-regime) model is a better description of flow on pedestrian facilities than the linear model.

Flow-concentration and flow-speed relationships can be derived from the speed-concentration relation by invoking the classical equation describing traffic flow, $q = u * k$, yielding the following:

$$q = u_f k - (u_f/k_j)\, k^2 \tag{3}$$

$$q = u\, k_j - (k_j/u_f)\, u^2 \tag{4}$$

Of all the studies mentioned above, the one conducted in 1966 by the Russian Engineering Construction Institute (MISI) is the most comprehensive in scope as it considered both quantitative as well as qualitative characteristics of the pedestrian traffic flow process [18]. In that study, classification according to the type of flow- “emergency”, “normal”, or “comfortable”- was suggested to reflect the effect of “psychological mood”. Based on a large number of observations of mass movements, the speed-concentration relation, for a horizontal path under normal conditions, was specified and calibrated as follows:

$$u = 57 - 217D + 434\, D^2 - 380\, D^3 + 112\, D^4 \tag{5}$$

where u is the average pedestrian speed in metes per minute, and D is the pedestrian stream’s concentration expressed as the occupancy ratio, the sum of pedestrians’ horizontal projections divided by the footway floor area, which takes values from zero to 0.92 [18].

Using 0.125 square meters as the average projection area of the human body, as established by MISI, the above relationship can be expressed as follows:

$$u = 57 - 27.125\,k + 6.781\,k^2 - 0.742\,k^3 + 0.027\,k^4 \tag{6}$$

where k is the pedestrian stream's concentration in persons per square meter (p/m^2).

The above relationship between speed and concentration was developed for a stream of pedestrians (with mixed types of people) moving along a horizontal footway under normal psychological conditions. For other types of flows, with different facility types and psychological moods, the basic formula above is adjusted by applying the respective correction factor. For example, to reflect the psychological state of pedestrians, the average speed of the stream along a horizontal path under emergency conditions is found by adjusting the one for normal conditions upward by a multiplier a_e, that is $u_e = a_e{}^* u$, where $a_e = 1.49 - 0.36D$ (or $a_e = 1.49 - 0.045^* k$) and u is the corresponding average speed for normal conditions (given by Eqs. 5 and 6). The corresponding relation for comfortable psychological conditions is $u_c = a_c{}^* u$, where $a_c = 0.63 + 0.25^*D$ (or $a_c = 0.63 + 0.03125^* k$). The flow-concentration curves for the different types of footways under normal conditions (e.g. doorways, upstairs and downstairs motions) are shown in Fig. 2.

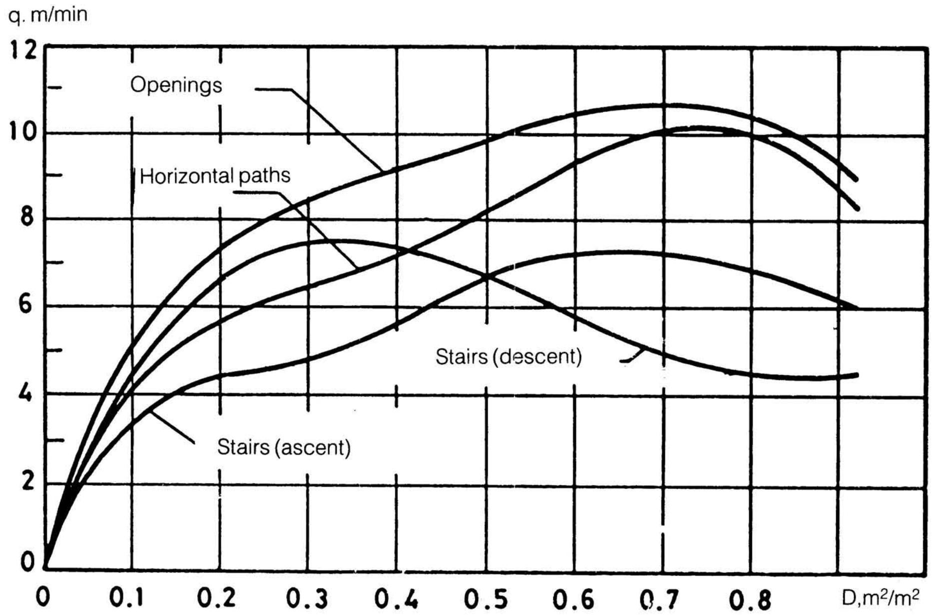

Fig. 2. Flow-concentration relations for horizontal path, stairs, and doorways under normal conditions [18].

Comparing the speed-concentration relation developed by MISI for a horizontal path to the other studies reported earlier, one notes that: 1) MISI's study observed a wider range of concentrations [Fig. 1a], and 2) the magnitude of the estimated free-flow speed is lower than that of the others. These differences may be attributed to the socioeconomic characteristics of the populations involved. On the other hand, the MISI flow-concentration relation bears some similarity to that of Hankin and Wright [19]. Each curve has two peaks: one at a concentration of 1.4 p/m^2, for both curves, and the other, higher peak, at a concentration of 4.3 p/m^2 for Hankin and Wright's model and 6 p/m^2 for MISI's.

MISI's study also classified pedestrian motion as a function of pedestrian concentration, as shown in Fig. 3, which superimposes the speed and the flow rate of a pedestrian stream, moving along a horizontal footway under normal psychological

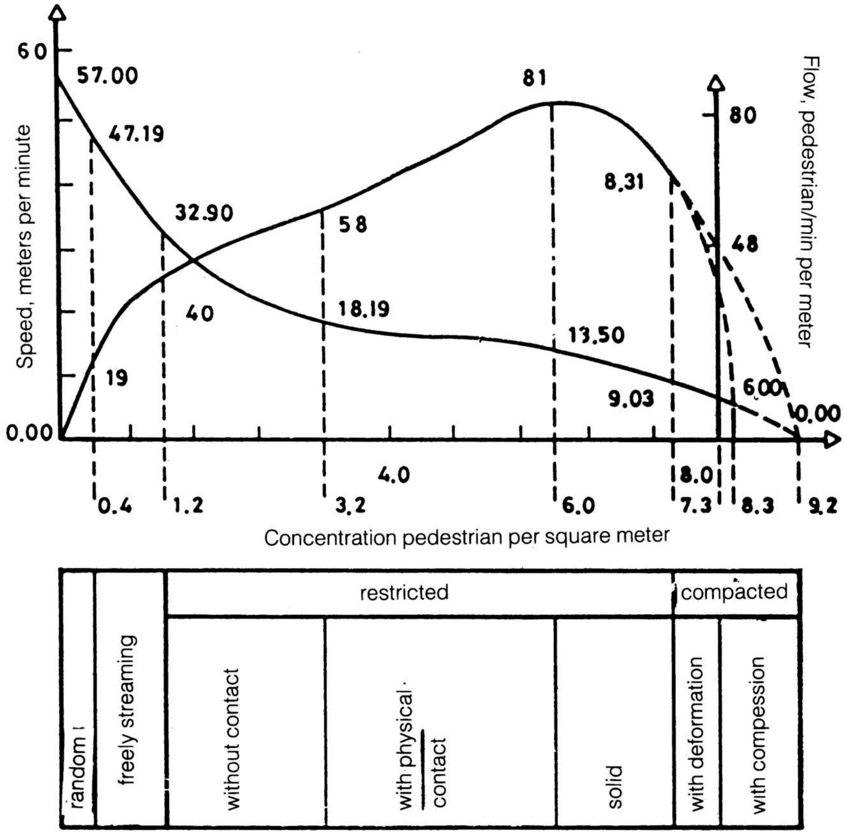

Fig. 3. Classification of pedestrian motion [18].

conditions, as a function of its concentration. A similar classification has been suggested by Fruin [4] and Oeding [20].

Other studies have suggested the use of the kinetic theory of gases to model pedestrian flow, such as Henderson [28], Henderson and Lyons [29], Henderson and Jenkins [30], and Henderson [31]. These studies advanced the proposition that the distribution of speeds of individual pedestrians in a crowd under different concentration conditions is analogous to the distribution of the speed of molecules in an ideal gas, i.e. Gaussian [e.g. 4,32]. These studies defined two distinct phases of pedestrian flow, based on the level of prevailing concentration: the loosely packed phase (or "crowd gas" at low concentrations, and the densely packed one (or "crowd fluid") at high concentrations. In the so-called gaseous phase, each individual is viewed as a prime gas particle, while two or more people moving together form a composite particle. Particles, prime or composite, are assumed to be statistically idependent of each other, in position and speed. Furthermore, three distinct energy modes of the pedestrian stream are defined: standing still, walking and running. Measurements of the speeds of school children, university students, and sidewalk pedestrians, for all energy modes, have shown that their statistical distributions were approximately Maxwell-Boltzmann in two dimensions, suggesting the applicability of Boltzmann transport theory to pedestrian flow.

However, this would require the pedestrian flow to be in a time invariant state (i.e. at equilibrium), and composed of statistically independent, nearly homogeneous prime particles (individuals) of the same sex and in the same energy mode.

A similar study [33], also suggested that pedestrian velocities at low enough concentrations follow Maxwell-Boltzmann velocity statistics in two dimensions. The study was based on speed measurements of pedestrians walking alone, in pairs and in groups of three. It was also found that the mean and the variance of the forward speeds decrease with increasing group size.

Crowd Behavior Studies

These studies deal with the behavior of large crowds, which occur under crowding conditions, and often involve extremes of human emotions such as excitement, fear, religious fervor, anger or exaltation. Because of the role of human emotion in these situations, several studies have been directed at the socio-psychological aspects of crowd behavior rather than its physical aspects. As such, these studies might have neglected the direct influence of a constructed environment on behavior, though they provide useful insights for the development of mathematical models of these phenomena. Other studies have dealt with human behavior with respect to the constructed as well as the behavioral environments. Both types of studies can be further classified into those that are primarily qualitative versus those that propose mathematical models of crowd processes. Qualitative studies are reviewed next, followed by a review of the relevant quantitative modeling studies.

Qualitative crowd behavior studies

Much of the initial interest of socio-psychologists in the field of collective behavior has centered on the study of the crowd [34]. Collective behavior has been defined as group behavior which originates spontaneously, is relatively unorganized, fairly unpredictable and planless in its course of development, and depends upon interstimulation among participants [35].

Crowd behavior is a major form of collective behavior. A crowd is a temporary collection of people reacting together to stimuli. Its members rarely know one another. Most forms of crowd behavior are unstructed with no rules, no traditions, no formal controls, no designated leaders, and no established patterns for the members to follow [36]. The basic elements in forming a simple crowd seem to be: 1) an object sufficiently interesting to focus attention, 2) interaction among the members, 3) a common mood resulting from interaction and 4) simple ideas or images shared by all by virtue of the experience in the crowd [37].

Several researchers have attempted to classify crowds and crowd behavior. Among them is Blumer [34], who classified crowds into four types. The first is the casual crowd, where onlookers come together spontaneously for brief periods when their attention is drawn to some commonly perceived event, as in the instance of a street crowd watching a performer in a store window. They do very little but view that event and are thus mainly a passive and fleeting aggregate of persons.

The second type is the conventionalized crowd which assembles for a specific purpose. Its behavior is essentially like that of the casual crowd, except that it is usually expressed in established ways. The Mosque (church) congregation is quiet and respectful; the fans at a ball game roar their approval and disapproval. It is this regularized activity that marks off the conventional crowd as a distinct type. The third type is the expressive, or "dancing", crowd, in which the subjective experiences of the members themselves are the principal features of attention. A highly emotional religious revival meeting is a an example. Its distinguishing trait is that excitement is expressed in physical movement primarily as a form of release instead of being directed toward some object.

Neither casual nor conventionalized crowds take collective action with respect to objects or individuals external to themselves. In contrast, the acting, aggressive, crowd is one that openly engages in more volatile forms of behavior directed toward persons, things, or events. For example, damage to property or injury to persons may result from externally focused behavior of an active crowd, such as a mob participating in a riot. The outstanding mark of this type of crowd is the presence of an aim or objective toward which the activity of the crowd is directed. It is this type of crowd which is the object of concern in practically all studies of the crowd [34].

On the other hand, Davis and Levine [38] have suggested that the "Public in Transit" constitutes a co-acting group, a term first used by Doob [39]:

> Persons who are simultaneously seeking approximately the same goal without competing or cooperating but who have an awareness of one another ... Incidental contacts are culturally prescribed but little or no coordination exists. Each person ... is concerned with himself and not with his relations to the ... group. [39, p.195].

In most socio-psychological studies of crowds, the mental states of individuals in crowd situations were considered as most essential for the behavior of crowds and masses [40]. One notable exception is Milgram and Toch [35] who gave a rather extensive and thorough review of the psychology of crowds and collective behavior, and also gave attention to the spatial and physical aspects of crowds:

> A comprehensive theory of crowds must take into account, in a systematic rather than metaphoric fashion, the role played by the physical conditions created by dense aggregates of people ... While a fully articulated theory linking the variables of macroscopic analysis has not yet been propsed, characterization of the crowd at this level may suggest important regularities. Moreover, this perspective lends itself to empirical inquiry. Spatial aspects of the crowd may be readily recorded with techniques of aerial photography, and time-lapse studies or motion picture films allow the temporal features to be recorded and carefully scrutinized ... Such methods may make it possible to predict, for example, the eventual size of a crowd on the basis of initial rate of aggregation – a question of considerable theoretical and practical import ... The densest crowds commonly found in day-to-day life are those in the subways of Tokyo. Pushers are employed to pack as many bodies as possible into subway cars. High density ... invariably creates problems of internal friction. In Tokyo, slippery coats are sold to subway riders to facilitate their movement through the tightly packed mass. [35, pp.517-518, 529].

Milgram and Toch [35] have identified a number of macroscopic properties of the crowd, including: 1) shape and rudimentary structure, 2) boundaries, 3) internal substructures, 4) polarization, 5) ecology, dependence on physical-environmental conditions, 6) crowd motion, 7) crowd size and its rates of growth and dispersion, and 8) crowd composition. In the following, these qualitative crowd behavior features are, in turn, briefly discussed, based mainly on the work of Milgram and Toch [35].

1. Crowd shape and rudimentary structure: Typical group configurations have often been noted in flocks of birds, schools of fish and packs of baboons [41,42], but little has been directed at human aggregations. Spontaneous human crowds tend to form rings, stable structures which can grow many layers thick. Physical constraints, such as the presence of walls or barriers, may prevent the full completion of the ring, but frequently arc segments can be discerned.

In a crowd, persons who arrive early tend to be at its center, while those who arrive late tend to be at its fringe. However, there will also be movement of the more ardent or involved members towards the crowd's center, resulting in fractionation strata, analogous to that resulting from the separation of heavy and light particles in a centrifuge. Thus, those who are most intensely motivated to carry out the crowd's purposes will be disproportionately represented at the crowd's structural core.

The inner area of the ring structure provides for the spatial separation between onlookers and the object of focus, such as a speaker. The larger the circumference of the inner boundary, the greater the number of individuals who can observe this object without being obstructed by the heads and bodies of other members. The inner space also highlights the functional difference between the focus of attention and onlookers. The dimensions of the inner space are related to a number of variables such as the object of focus' elevation with respect to the crowd and degree of attraction or repulsion, the size of the ring, and the pressure from those in the rear.

2. Crowd boundary: The boundary of the crowd structure, which defines its limits, is characterized by its permeability and degree of sharpness. Whether a crowd boundary is open or closed to new persons depends on both physical and ideological factors. For example, a densely packed ring surrounding a circus performer may not allow others to get close to the core but allows them to build around the outer fringe. Furthermore, crowds need not be fully open or closed, but may display selectivity along ideological lines.

3. Crowd internal substructures: A crowd that appears to be undifferentiated may on closer examination possess internal boundaries dividing it into several subgroups. Lamination effects are common in crowd formations. Most crowds cannot be thought of as an aggregation of isolated points, since a fair proportion of the participants are likely to have specifiable kinship or friendship ties to one or more other participants in the assemblage, forming substructures that govern the participants' behavior.

4. Crowd polarization: Polarization of a crowd is defined as the extent to which all of its members face or focus their attention on one object. It is used as a rough indicator to specify the boundary of the crowd and to delineate subgroups within it. As one moves outwards from the center of the crowd in concentric rings, the proportion of people polarized toward the center may drop off. A quantitative measure of polarization was suggested by Milgram and Toch [35], where each member of the crowd is assigned a polarization value of one if his/her eyes are focused towards the object of interest, and zero otherwise. The degree of polarization of the entire crowd can then be represented by the fraction of the sum of crowd members' polarization values to the total number of participants. No polarization value defining the exact boundary of the crowd has been given.

5. Crowd ecology: The shape of the physical environment radically affects crowd behavior. Panic, for example, depends on a special set of physical conditions. These occur when an aggregation of people is enclosed in a space that has limited exit possibilities, which would allow only those who rush for them first to escape, whereas those who are behind get trapped. On the other hand, it has been observed that when a noxious stimulus, such as a fire, occurs in a totally enclosed area where there is no possibility of escape, panic does not develop [43]. Also, when the escape routes are not limited but fully open, panic rarely develops [44].

6. Crowd motion: Crowd movement can be synchronized, in that all crowd members begin to move at the same time, like marching soldiers. However, the motion of a crowd is more often staggered, in that a person waits for the one in front to make his/her move before starting. The inefficiency of the staggered motion relative to the synchronized one is clear, for in the former the time required to move the crowd a given distance is a function of the sum of all the members' movement times, as opposed to that of a typical marching individual in the latter.

If all members of the crowd are moving in the same direction, crushes will occur if a person moves forward before the one ahead has completely vacated his/her spot. More generally, the number of collisions between individuals in a crowd is a function of the crowd concentration, the members' speed, and the number of directions pursued by the participants.

7. Crowd size: A crowd that is beginning to form around an object of interest will grow to an ultimate size that is limited by the concentration of potential participants in the immediately surrounding area, and by other factors, such as the time of day and the diminished visibility caused by the initial onlookers.

8. Crowd compositon: Finally, the characteristics of the people who make up the crowd, such as social class, age, sex, literacy, religion, and geographical origin are of importance to understanding crowd behavior. The composition of crowds is functionally related to its actions, and its precise makeup may play a very important role in determining the form of collective behavior that arises. For example, combative riots may not occur with an assemblage containing a high proportion of women and children, since their presence would tend to dampen the movement towards violence.

Crowd behavior models

These studies have sought to develop models of individual behavior in a crowd, recognizing the constructed as well as the behavioral environments. Wolff [45] has observationally shown the need to include spatial measurements in such types of behavioral studies, emphasizing the use of dynamic models of individual behavior, but without proposing any specific model. His study considered inter-personal distance, level of concentration, and the width of the sidewalk to explain pedestrians interactions, coordination and cooperation in these environmental settings.

Wolpert and Zillmann [46] have developed a simulation model of the distribution of information under panic and the resulting movement of individuals. The model employs four different mechanisms: search, choice, response to threat or appeal, and interdependencies involving conflict. It assumes that a person who is faced with a threat, e.g. a fire, will estimate the respective times (distance/speed) to reach an exit, for the fire to reach him/her, and for the fire to reach the exit. The potential field of escape routes for the person is searched for other people who may be competing for the same exit. An obstruction value, expressed in time, is estimated and used additively to modify the estimate of the escape time. The person will panic if the time needed to escape exceeds that for the fire to reach him/her or the exit. The subject not in panic approaches the exit which offers the greatest safety margin, whereas one in panic follows a decision rule which is based upon more limited cognition.

Stilitz [47] has explored the qualitative effects of stationary pedestrian groups on the movement patterns and rates of pedestrian flow in congested spaces. Under certain conditions stationary groups impede movement and diminish the effective width of key movement channels. In a later study, Stilitz [48] examined pedestrian behavior in high concentration circulation spaces, in an attempt to relate the patterns of pedestrian behavior to the physical attributes of spaces that become congested. The study suggests a conceptual framework which describes how attributes of the built environment and those of pedestrians interact to determine movement and flow patterns. From observations conducted in the London Underground, the study found that the three most important characteristics of pedestrians are that they tend to take shortest paths, avoid collision, and have preferred speeds.

Baer [49] has built a disaggregate simulation model of multidirectional pedestrian movement under high concentration and intensive traffic (i.e. when crowding occurs with movement). The model consists of: 1) a stochastic element, which generates the individual's attributes, such as arrival and departure times, entry and exist points, route, physical characteristics and preferred speed, and 2) a discrete time-step processor which handles movement of the individuals present in the system at any given time. Between their birth and death, persons, in the model, are guided through the physical and the behavioral environment by deterministic path-selection algorithms. The model assumes that each person has a distinct point of entry into the space of interest, an individual goal, a defined route between the entry point and goal (goal direction), and personal characteristics in terms of preferred speed and area of horizontal projection (a circle). The individual's route is given by a sequence of corners of the space (subgoals) around which the route leads. The individual is assumed to go through the following process in determining his/her next movement, in each time step $\triangle t$, of the discrete-time simulation:

1) The initial range of perception (a circle) is determined by the distance an individual would walk at his/her preferred speed.

2) Starting with the initial circle of perception, its sectors are sarched for possible collision-free movement. Feasible sectors are then evaluated for minimization of a) the angle of its deviation from the goal direction, and b) the distance from the endpoint of the proposed movement to the goal. If no feasible solution exists, the range of perception is reduced, and the above search and evaluation process is repeated until the individual finds at least one possible move. The length of that move is determined by the reduction of the range necessary to find a feasible sector.

3) However, if more than one feasible sector exist for the individual to move into the one that allows getting closest to the next subgoal is chosen.

No explicit speed-concentration relation is employed in Baer's model. However, individuals are assumed to adapt their velocity to the local concentration, thereby implicitly giving rise to a speed-concentration relationship.

Boles [50] has also developed a disaggregate simulation model of sidewalk traffic, incorporating both the physical system's attributes and the human component characteristics. The creation and orderly flow of pedestrians within the model is contingent upon five characteristics: the pedestrian's 1) entry point and location, 2) goal point, 3) direction, 4) velocity, and 5) depth of field of perception. Given the sidewalk dimensions, which can be viewed as a coordinate plane, and using both entry and goal points, it is possible to represent the shortest path to the goal as a straight line. Scanning a pedestrian's field of visual perception is then performed to determine possible conflicts, such as personal space violation or body collision, and consequently correcting a pedestrian's path or speed to avoid such conflict.

Hirai and Tarui [51] have constructed a mathematical model of crowd behavior under panic. The model considers mass psychology as well as the effects of the environment, such as the presence of signs or symbols to guide the crowd to exits in emergency, wall configurations, and the locations of emergency exits. By analogy to Newton's second law, the model relates acceleration to the various forces acting on the crowd. The mathematical model is expressed in the form:

$$m_i\,(d^2x_i/dt^2) + \mu_i(dx/dt) = F_{1i} + F_{2i} + F_{3i} \tag{7}$$

where m_i, μ_i, and x_i are, respectively, the mass, coefficient of viscosity, and n-position vector of individual i, i = 1, ... , I. F_{1i}, F_{2i} and F_{3i} are external forces acting upon individual i. F_{1i} is a force required by individual i to form a group together with other individuals and to move forward; F_{2i} is a force exerted by the environment around individual i; and F_{3i} is a random force acting upon individual i. Each of these forces is, in turn, expressed by the sum of several forces, i.e.:

$$F_{1i} = F_{ai} + F_{bi} + F_{ci} \tag{8}$$

where F_{ai} is a force causing individual i to move forward at a constant speed, F_{bi} is an attraction or repulsion force acting between individual i and other individuals, and F_{ci} is a force acting upon individual i so as to control each of his/her movement at the same speed and in one direction. In addition,

$$F_{2i} = F_{wi} + \Sigma_k(F_{eik} + F_{fik}) + F_{gi} + F_{hi} \tag{9}$$

where F_{wi} is the repulsion force from the wall, F_{eik} is the attraction of a guiding sign or symbol k indicating the location or direction of an exit, F_{fik} is the same as F_{eik} but acts only upon the individual with prior knowledge of such signs and symbols, F_{gi} is the attraction of an exit and F_{hi} is a constant force causing individual i to move away from a site where panic has arisen.

The above model was calibrated using data from a controlled experiment conducted by the Tokyo Fire Department to observe how rats in a wire cage behave and escape through an exit when an electric shock is applied to them. The reasoning for using such data to calibrate the model was that the mental state of paniced people is such that their behavior may be similar to that of animals, i.e. reflexive, irrational, and instinctive.

Fruin [1] has proposed a conceptual systems analysis framework to evaluate the factors contributing to crowd disasters, and to establish appropriate possible countermeasures. In his study, crowds are viewed as a system consisting of four fundamental elements: time, space, information and energy (or crowd force). Crowd force is defined as that created by massed pedestrians, resulting in crowd crushing pressures, and the injury and death associated with a crowd disaster. Thus crowd disaster is defined, according to Fruin, as: "the rapid coming together of a group of persons in a constructed space with sufficient mass and force to cause human injury or death." In the discussion of crowd forces, Fruin explains qualitatively how the combined pressures of massed pedestrians and shock wave effects through crowds at some critical concentration level produce forces which are impossible for individuals, or even small groups of individuals, to resist. Incidents of persons being literally lifted out of their shoes and of clothes being torn off, are the result of the forces involved in the crowd. Pushing within the crowd results in compounding and magnification of the forces acting on the crowd and produces the momentum responsible for the extreme crowd pressures generated in crowd disasters. When the crowd is densely packed and forces are applied, it performs as an almost incompressible fluid medium, with shock waves moving through it [1]. Table 1 is a summary of Fruin's crowd disaster system elements, causes, and countermeasures.

Harlow and Sandoval [52] have adapted a mathematical model originally developed for turbulence in fluids to describe the general mechanisms and processes underlying mob behavior. They studied the dynamics of four variables believed to play a crucial role in group behavior: individual levels of excitement, e, and fear, f; relative position of an individual in the crowd, **x**; and his/her walking speed, **u**. In addition, the model includes intrinsic (constant in time for each individual) susceptibilities for excitement and fear, s and s_f, which differ from person to person. To describe the variations of **x, u,** e, and f, the model uses linear interaction terms between the individual and the mob, representing the lowest order Taylor expansion of general interaction functions of the following form:

Table 1. Crowd disasters system evaluation [1]

System element	Causes/characteristics	Countermeasures
Time	Immediate pedestrian demand exceeding processing facility and/or processing personnel capacity, rapid accumulation. queue buildup.	– Temporal dispersion of demand; – Provision of processing elements/ personnel $\geqslant$ demand & allowances for variation. – Demand metering under close control.
Space	Space limited, traffic flow constricted (bottleneck), average individual personal area occupancies below 2 square feet, approaching area of human body.	– Spatial dispersion of traffic flow. multiple portals for ingress, egress, space configuration; – Adequate traffic flow capacity and queuing space.
Information	Information provides crowd movement and direction, momentum; may induce behavioral panic or craze.	– Information for spatial and temporal dispersion through ticketing, signs, announcements; – Avoidance of group competition producing behavioral panic, crazes.
Crowd force	Crowd mass approaches characteristics of fluids, shock wave effects, crowd pressures sufficient to cause human injury.	– Crowd management communication. – All countermeasures above; – Prevention of rapid crowd movement to reduce momentum, shock wave effects.

$$de/dt = -D_e\, e + BsE + N_e \tag{10}$$

$$df/dt = -\, D_f\, f + B\, s_f\, E + N_f \tag{11}$$

$$\mathbf{u} = -\, C\, \nabla\, \rho + A\,(e - f)\, \mathbf{L} - \mathbf{D_u} \tag{12}$$

$$d\mathbf{x}/dt = \mathbf{u} \tag{13}$$

in which $D_{e,}$ $D_{f,}$ and $\mathbf{D_u}$ are decay functions, N_e and N_f are environmental source terms of prescribed functions of space and time, but not ordinarily of the individual or collective properties of the mob itself, E is a measure of surrounding mob excitement, which depends on the individual's location reltive to the other members of the mob, **L** describes attration to regions of largest mob excitement, ρ is the logarithm of the crowd concentration, while A, B, and C are parameters that modulate the intensity of the interaction between an individual and the mob. Variation in excitement and fear thus each have three contributing sources: decay (e.g., from boredom), a mob-induced source, and an environmental source (e.g., from the sounding of a police siren or the incitement of a speaker).

The collective variables introduced in the above equations, namely, E, ρ, $\nabla\,\rho$, and **L**, vary with position and time. These quantities are calculated as follows:

$$E(\mathbf{x_i}) = \Sigma_j\, g(a_{ij})\, e(\mathbf{x_j}) \,/\, \Sigma_j\, g(a_{ij}) \tag{14}$$

$$\rho(\mathbf{x_i}) = (\rho_0\, g_0 \,/\, \pi)\, \Sigma_j\, g(a_{ij}) \tag{15}$$

$$\nabla\rho(\mathbf{x_i}) = \{\Sigma_j g(a_{ij})\, (\mathbf{x_j} - \mathbf{x_i}) \,/\, a^2_{ij}\}/\Sigma_j g(a_{ij}) \tag{16}$$

$$\mathbf{L}(\mathbf{x_i}) = \{\Sigma_j\, g(a_{ij})\, e(\mathbf{x_j})\, (\mathbf{x_j} - \mathbf{x_i}) \,/\, a^2_{ij}\}/\Sigma_j\, g(a_{ij}) \tag{17}$$

in which a_{ij} is the distance between individuals i and j; $g(a_{ij})$ is the communication function between individuals i and j, which may take the following form: $g(a_{ij})=\exp(-g_0\, a^2_{ij})$; and ρ_0 and g_0 are scaling factors.

This model does not appear to have been calibrated, but can be taken as a basic framework upon which to build and test more elaborate models. In general, the use of hydrodynamic modeling approaches is based on the observation that a crowd appears to behave like a continuous medium and that it is relatively incompressible. Many of the basic characteristics of turbulent flow exist in crowd flow, such as randomness and irregularity in fluctuation. Currently there does not appear to be a generally accepted analytical model that describes the complete nature of turbulence. However, one can benefit from this analogy once an empirical model is found, as demonstrated by this study, with the help of dimensional analysis and statistical methods.

Hajj Studies

Unfortunately, very limited research has been directed at crowd behavior and movement during the Hajj. Most of the Hajj research studies conducted in the past two decades have dealt mainly with its historical development, growth and administration [53-56]; demographics [57,58]; physical planning problems [59]; transportation planning [60,61]; logistical problems, control and management, such as transportation and fire [62]; housing and accommodation [63-65]; architectural and urban patterns [66]; land use patterns [67]; and tent cities characteristics [68,69]. Of these studies, the last three have touched on problems of pedestrian crowding, especially in the Jamarat area. However, their treatment of the problem was ad hoc in nature and not based on quantitative, systematic analysis.

The Hajj is, undoubtedly, the largest annually recurring mass confluence of people in the world. Within it, four specific locations experience the heaviest crowd movements, which occur during:

1) the departure from Arafat to Mina (through Muzdalifah);

2) the performance of "Tawaf", where pilgrims circumambulate the Ka'bah, or the black cube located in the Sacred Mosque of Makkah, seven times;

3) the performance of "Sa'ee", where pilgrims walk (briskly) seven times between two hills spaced about 400 meters apart, next to the Sacred Mosque of Makkah, which usually follow the Tawaf; and

4) stoning the devil at the Jamarat area in Mina.

Crowd behavior and movement in these four locations have been the subject of several research studies. The Hajj Research Center (HRC), of Umm-Al-Qura University, Makkah, Saudi Arabia, conducted several studies on pedestrian movements between Makkah, Mina, Muzdalifah and Arafat [70-72]. The 1982 HRC study [72] conducted a survey to estimate the total number of pilgrims who walked between the different rites, as well as those who used other modes of transportation. Using the models of pedestrian traffic flow developed by Hankin and Wright [19], the study established the physical requirements (in terms of total width) of footways between these sites. Its use of speed-concentration-flow models originally calibrated for London

don subway passengers, who exhibit different socio-economic and physical characteristics, is questionable for the mix of pilgrims encountered in Makkah.

At the center of the Sacred Mosque of Makkah stands the Ka'bah which is supposed to be circumambulated, seven times in a counter-clockwise direction, by every pilgrim during the Hajj, in the ritual called Tawaf. The Tawaf area is circular, with the Ka'bah at its center and an outer boundary having a radius of about 48 meters. Gibson [73] attempted to relate the time it takes to perform Tawaf to the volume of pilgrims performing the ritual at a given time, with the intent of using this relation to ascertain the capacity of the Tawaf area. Tawaf times were estimated by tracing individuals as they performed the rite and recording the corresponding completion times. At the same time, volumes of pilgrims performing Tawaf were recorded by four different methods: manually, and using time-lapse, still and aerial photography.

Haug, Gawenat and Rasch [74] conducted what appears to be the first analytical study to evaluate capacity of the existing Tawaf area. The study utilized pedestrian traffic flow models developed by MISI [18], and assumed that pilgrims' movement during Tawaf is circumferentially homogeneous and steady, meaning that each pilgrim moves in the same circle around the Ka'bah. While the pilgrims' concentration is assumed to be constant along a given circle, it may vary from one circle to another along the radial direction.

The study evaluated the effects of a number of measures aimed at increasing the Tawaf capacity, mainly by manipulating the shape of assumed pilgrims' concentration profiles along the radial direction. It should be noted in this regard that the assumptions of pilgrims' axisymmetric motion and concentration distribution are strong ones. These assumptions tend to ignore the actual mechanics of the process being modeled. It would have been more useful if the study considered: variations of pilgrims' concentration in the circumferential direction, non-steady pilgrims' motions, allowance for radial fluctuation of pilgrims' positions during circumambulation, and non-circular motion around the Ka'bah (actual motion is approximately elliptical).

A more comprehensive study of the Tawaf process was conducted to understand its underlying mechanisms, estimate the Tawaf capacity, and characterize crowd behavior while performing this rite [75]. Data obtained in this study include the speeds of pilgrims at different concentration levels, pilgrims' concentration and speed profiles along the radial direction from the Ka'bah, and qualitative as well as quantitative measures of crowd behavior at specific locations in the Tawaf area. The quantitative crowd behavior measures include stopping times and the spatial profile of pilgrims waiting to kiss the black stone, located in the corner of Ka'bah that marks the starting line of each of the seven laps of Tawaf, as well as the times of frequent pilgrims' stopping at this starting line. Furthermore, stopping times at Abraham's prayer station, in front of the Ka'bah, and its effect on others Tawaf times, and the percentage of pilgrims walking against the main flow, to reach the starting line and thus start their Tawaf, were also quantified. A mathematical model specific to this particular situation was developed and partially calibrated. The model specifies a speed-concentration relationship as well as the functional form of the concentration profile along the distance away from the Ka'bah [76].

The third overcrowded ritual of the Hajj is Sa'ee, which takes place in two tracks, each 10 meters wide for each direction of movement, between two hills. In the above mentioned study of Gibson [73], an attempt was also made to establish a relation between the time required to complete Sa'ee and the corresponding pilgrims' flow rate, but with little success.

Hence, another study was carried out to analyze pilgrims movement during Sa'ee [77]. Data collected in that study included volumes of pilgrims performing Sa'ee in a given direciton, and the time it takes a pilgrim to complete one round-trip between the two hills, i.e. one cycle (total Sa'ee has 3.5 cycles), for a random sample of pilgrims. To estimate the total Sa'ee time, the study assumed that the time required to complete one cycle of Sa'ee does not change from one cycle to another. Thus, it was possible to calibrate a model for Sa'ee time as a function of the flow rates of pilgrims performing this rite.

Although the Jamarat area is probably the most serious bottleneck of the Hajj, where pilgrims suffer a great deal due to congestion and overcrowding, it has received little attention in the research literature.

The Hajj Research Center carried out a major study which identified the problems at the Jamarat area, investigated the causes, and then proposed some countermeasures to improve its performance [78]. Some of the pertinent problems identified by that study include:

1) high rates of fatalities, as a result of heat stroke and exhaustion, of being trampled under other pilgrims' feet and asphyxia; difficulty in breathing and injuries, as a result of being hit by other pilgrims' pebbles, collision with other pilgrims, and crushing in the crowd; and dizziness, in addition to the problems mentioned for fatalities;

2) extraordinary difficulties involved in squeezing into and out of the three

Jamarat rings during peak periods, to the extent that some pilgrims escape the crowd pressure by jumping off the jamarat bridge (10 meters high) onto the ground; and

3) increase in the time required to perform the rite of stoning, during overcrowding, up to six times what it takes during the off-peak period.

The causes of these problems were believed to be the following:

1) peak period demand which exceeds the maximum throughput of the system, estimated to be 200,000 pilgrims per hour (both levels);

2) movements of pilgrims in two opposite direcitons, in a system designed to be a one way movement scheme, which results in a reduction of the system's throughput;

3) the limited throughput of each of the three Jamarat rings as a result of non-uniform distribution of pilgrims around the Jamarah ring;

4) the aggressive behavior of some pilgrims who move in groups and push their way through as one unit; and

5) the slow response of emergency medical services to accident calls, because of the difficulty in making their way to the location of the accidents.

The study proposed countermeasures in five major areas, namely: engineering the physical aspects of the Jamarat area, pilgrims' education, crowd control, medical services, and improvement of the environmental conditions in that area. The engineering solutions stressed improving the structure's design in order to encourage pilgrims to use it as a one-way movement system, control the pilgrims' entry rate, spread the pilgrims uniformly around each of the Jamarat, and diffuse those pilgrims moving together as a group. The crowd control measures suggested by the study were limited to the need for trained personnel, at designated entrances and exits, to guide arriving and departing pilgrims to entrances and exits therefore enforcing a one-way movement system. Although the study was successful in qualitatively characterizing the problems encountered in the Jamarat area, it did not propose any quantitative model to characterize pilgrim flow in the Jamarat area.

Hence, a study was conducted at the Jamarat area to manually count the pilgrims coming for stoning at both levels of the Jamarat bridge, and determine their flow rates [79]. The study revealed that 13%, 13.8% and 10% of the total pilgrims performed the stoning during the peak hour for the first, second and third days of stoning, respectively. Furthermore, during these three days, respectively, 35%, 34% and 33% of the pilgrims performed stoning from the upper level of the Jamarat bridge (as opposed to the lower level). During that time, the maximum throughput of the Jamarat system was observed to be about 190,000 pilgrims per hour for both levels, and 69,000 pilgrims per hour for the upper level only.

A macroscopic model of the flow of pilgrims between the three jamarat rings, under heavy traffic conditions, was developed by Al-Rabeh and Selim [80]. This model defines two physical regions for each Jamarah, namely a close region, which is occupied by pilgrims who are involved in the act of stoning, and a far one, where pilgrims who intend to proceed to the close region are waiting for such opportunity. A block diagram, for the Jamarat system, was then constructed to describe the movement of pilgrims from the far region of the first Jamarah to its close region, then to the far region of the second one and so on. Furthermore, the fraction of pilgrims opposing the main traffic stream was modeled explicitly in the pilgrims flow chart. Although this model has shown, mathematically, the negative effect of pilgrims opposing the flow on the Jamarat system performance, it did not attempt to establish the throughput of each of the three Jamarat rings. Instead, the model simply assumes an average value per unit time for these throughputs, such assumption limits the model's ability to characterize crowd behavior and movement at the Jamarat.

Later, Selim and Al-Rabeh [81] developed an optimization model that casts the problem of regulating the pilgrims flow into the Jamarat bridge as that of minimizing the cost/penalty of control such that the number of pilgrims in the neighborhood of each Jamarah does not exceed some predetermined limit, which is proportional to the area of the region around the Jamarah ring and the maximum safe crowd density. The model requires as input certain crowd characteristics such as their number, the percentage interested in admission at different times, and the walking time between the three Jamarat rings. In this model, the throughput of each Jamarah is considered as an increasing function of the average number of pilgrims present around the ring, but with an upper-bound that depends on the configuration of the jamarah bridge and the ring surrounding the Jamarah.

Finally, the author developed a model of the dynamics of crowd behavior and movement, with particular reference to the Jamarat system [82]. The dynamics of crowd behavior and movement around an individual Jamarah ring were modeled. The model consisted of a set of simultaneous differential equations describing the principal processes that govern the dynamics of the system. These equations were solved numerically using a discretization of space and time, yielding a profile of the system's evolution. The use of the model was illustrated by examining the effect of different possible facility design and control strategies on the system's performance. Field data collected in connection with this study provided the basis for calibrating the model's principal relations, including a speed-concentration relation for multidirectional movement, which appeared to be unprecedented in the literature [83-85].

Concluding Remarks

In this paper, a review of previous research on: 1) steady-state pedestrian movement under normal conditions, and 2) crowd behavior was presented. It can be concluded, based on studies of the first type, that the theory of pedestrian traffic flow, for orderly movement under normal conditions, has been sufficiently developed to reflect the actual behavior of foot traffic flows in such context, and thus can be adopted for design and control purposes.

On the other hand, the review revealed that several, mostly qualitative, studies on crowd behavior have been directed primarily at its socio-psychological aspects. The focus of these studies has been on the mental states of the crowd participants, rather than the physical aspects of the crowd. Other studies that have dealt with crowd behavior with respect to the physical as well as the behavioral environments, were also presented in this review. In these studies, different modeling approaches and analogies have been used by researchers in their attempt to quantify human behavior in a variety of crowd situations (e.g. panic and mob); but the review revealed that none of these models appears to have been observationally calibrated.

The review of relevant Hajj studies presented in this paper showed that very limited research has been directed at crowd behavior and movement during the Hajj. With regard to the Jamarat system, although the studies by the Hajj Research Center (HRC) reviewed above provided a good qualitative description of the problems encountered by pilgrims in the Jamarat area, the model developed by the author [82-85] appears to be one of few attempts to characterize pilgrims behavior there. Enhancements to this first generation model are badly needed in lieu of the difficulties currently encountered by pilgrims and those responsible for the mangement of their movement; especially after the tragedy of the 1990 pilgrimage season where more than 1400 pilgrims were killed in a pedestrian tunnel, and that of the 1994 pilgrimage season where around 400 pilgrims were crushed at the Jamarat bridge.

The limited body of disparate studies reviewed above does not provide a sufficient technical basis for dealing with crowd movements at special events, leaving considerable gaps in the knowledge base and methodological capabilities pertinent to this problem. At present, (1) no equations exist specifying relationships between crowd behavior, B; crowd characteristics, C; facility design and layout, F; and management practices, M (Eq. 1), and (2) neither standardized definitions of variables to be measured in the field, nor standardized methods for reliably measuring these variables are available [2].

The review presented in this paper suggests that additional research should be directed to the important topic of crowd behavior and movement in general, and that occurs during the (annual) Hajj in particular. For example, the modelling approaches suggested by studies [81] and [82-85] should be continued and enhanced by relaxing the assumption of deterministic behavior and introducing stochastic elements in the modelling process. In addition, pilgrims safety (crushes or crowd pressure) was never modelled explicitly, rather an excessive concentration measure (concentration exceeding the jam concentration where packing takes place) was used in study [82] as a proxy for crowd pressure. It would be useful to directly relate some measure of crowd pressure to the prevailing concentration, based on the joint measurement of both variables in the field. Another possible area of experimental research would be to investigate the effect of providing the crowd with real-time visual information regarding the prevailing concentration profiles in different parts of the facility.

The challenge for any future research on this subject, then, is to develop useful means for predicting normal crowd behavior, and for enabling facility managers and designers to evaluate various scenarios before costly mistakes are made.

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