Improving Construction Safety by Providing Positive Feedback on Backup Alarms

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Abstract: Federally mandated backup alarms and safety management have been unable to eliminate fatalities and injuries due to maneuvering trucks and mobile equipment on construction sites. Workers appear to ignore the alarms as part of the general noise level. When reversing, drivers and equipment operators tend to depend on the alarm's effectiveness to clear areas in which drivers have limited visibility. Using human factors analysis, the problem was recognized as one of decremented vigilance, a person's natural inability to sustain attention without positive feedback. This paper presents experimental data on the use of a simulated, discriminating, personal alarm activated by a short range, directional transmitter to encourage safe behavior. During the experiment there was a significant increase in response time, as expected, for the conventional backup alarm and a decrease in response time for the discriminating personal alarm. The proposed backup alarm system has the potential to eliminate on-site vehicle/equipment accidents.

INTRODUCTION

The construction industry is one of the most dangerous in the nation. The construction industry has reported a high incidence of injuries involving the maneuvering of trucks and mobile equipment on construction sites (Bureau 1992). After years of collecting data on fatalities and injuries due to trucks and mobile equipment, the federal government mandated (Code of Federal Regulations 29 CFR 1926.601 and 29 CFR 1926.602) the use of backup alarms for all trucks and mobile equipment in the construction industry. The electronic alarms were required to be audible above the surrounding noise level and activated whenever a vehicle was put into reverse gear. Employers were responsible for ensuring that the alarms were operational before allowing the vehicle to be started. The safety requirements were authorized by the Construction Safety Act of 1962 and was included in the Occupational Safety and Health Act of 1970. However, fatalities and injuries are still occurring. About 13% of construction fatalities are currently related to industrial vehicles and equipment (Bureau 1992).

However, after years of experience with alarms and other safety measures, about 6,500,000 workdays are lost each year in the construction industry because of injuries. The incidence rate of fatalities during 1989 and 1990 were 22.4 and 20.6, respectively, for 100,000 full-time workers (Bureau 1992). The incident rate for injuries and illnesses for the same period was 14.3 and 14.2 cases per 100 full-time workers. Data on specific injuries and fatalities related to the effectiveness of alarm systems are not collected or recorded at the federal or state level. [Refer to Table 1 for the Bureau of Labor Statistics (Bureau 1992) data.]

RESEARCH OBJECTIVES

The objective of the present research is to determine whether warnings received on a discriminating personal alarm requiring positive feedback would be more effective than warnings from a conventional backup alarm. The discriminating alarm will only be activated when a worker is in possible danger from moving vehicles. The worker must physically silence the activated personal alarm; this positive action recaptures the worker's attention and forces him or her to find the source of the alarm. The act of silencing the alarm, positive feedback, is expected to change the worker's response to alarms from passive acknowledgement to an active response, and significantly reduce the incidence rate of on-site accidents.

BACKGROUND

Ninety eight percent of all accidents are caused by unsafe behavior. Workers injured on the job have probably committed the same unsafe act many times before getting injured (Watson 1986, Heinrich 1980). In the construction industry it is a common, but unsafe, practice to mix workers, heavy mobile equipment, and trucks in confined areas. Often, equipment operators work with very limited visibility and must depend on backup alarms to warn workers on the ground.

The general construction environment tends to encourage unsafe behavior. For example, noise levels tend to be high, in the 95–100 dBA range (Helander 1991), facility components must be constructed above the ground before safety barriers can be erected, and work must be performed on a very rough site. Conventional backup alarms intended to warn workers on the ground are no more than nondirectional area-wide announcements that a vehicle has changed into reverse gear. These alarms add to the noise level. The alarms are not directed toward any specific group of workers. Workers must use senses other than their auditory senses (e.g., visual, tactile), to interpret the environment and cues from coworkers to assess potential hazards from moving equipment. However, the auditory sense is still the primary sense used to detect such hazards.

A California Department of Industrial Relations study (Helander 1991) noted that over a period of 3 yr, 15 deaths were caused by backing trucks, graders, loaders, and other heavy equipment. Four major factors were involved in these accidents (1) inoperative backup alarm; (2) construction noise that masked the sound of the backup alarm; (3) poor visibility; and (4) worker inattention.

Vigilance Decrement

In many situations workers focus their attention on assigned tasks and exclude distracting noises. The possibility of injury from backing mobile equipment forces them to divide their attention between the task and awareness of the movement of mobile equipment in their vicinity. A worker's ability to perform this second task declines over time because of the concentration needed to perform the primary task. Attention can be maintained on the second task with reinforcement; for

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TABLE 1. Number and Rate of Occupational Injuries and Fatalities

Employment (×1,000)	INJURIES PER 100 FULL-TIME WORKERS				FATALITIES PER 100,000 FILL-TIME WORKERS			
	Injuries/Illnesses		Lost Workdays		Fatalities		Incidence	
1990 (1)	1989 (2)	1990 (3)	1989 (4)	1990 (5)	1989 (6)	1990 (7)	1989 (8)	1990 (9)
5,135.80	14.3	14.2	6.8	6.7	780	700	22.4	20.6

example, something that requires a positive response by the worker or the worker being able to look around and find a vehicle moving into the same work area. The general problem encountered by construction workers is known as a decrement in vigilance, which is the basic human characteristic of being unable to sustain attention over a prolonged period of time. There are several theories explaining the vigilance-decrement phenomena, some of which help explain fatalities and injuries that continue to occur on construction sites. After a prolonged exposure to alarm signals, workers appeared to become accustomed to the alarms (Kryter 1970) or filtered out (Warm 1984) annoying signals. The arousal level may be high at the beginning of any project; however, over time the stimulus fails to attract the worker's attention (Warm 1984). Workers expect mobile equipment and vehicles to follow certain paths on the site, or they work in nonthreatening areas based on their vague knowledge of the site and the movement of vehicles. Departure from these patterns and paths can increase the potential for accidents (Baker 1959).

Positive Feedback

Positive feedback increases the prevalence of safe behavior. Komaki et al (1978) and Sulzer-Azaroff (1978) were the first to demonstrate this technique to modify behavior. Many others have obtained convincing results showing that safety-related behavior can be modified effectively. Based on these studies, two basic types of feedback have been defined; that from the outcome of the behavior, and directly from the behavior (Saarl and Nasanen 1989).

Channels of Communication

According to the Treisman (1969) model, a person can focus on a single channel of communication, and the various types of information received through that channel will be rapidly processed in parallel. If information sources are separated by more than one degree from the viewpoint of the receiver, another communication channel is formed. Information received from different channels is processed in series, which tends to be slower and less efficient than parallel processing. People subjected to more than one channel of communication are forced to allocate mental resources to each channel, and experience mental fatigue. The effects of the diminishing allocation of resources and mental fatigue is increasing decrements in vigilance.

Controlling Hazards

Dawson et al. (1982) provided an analytical framework to develop strategies to control hazards, which possesses strong implications for construction projects. In considering the hazards related to backup alarms on construction sites, the most likely strategy would be containment. In the simplest terms, this type of hazard is really an interaction problem between workers on the ground and equipment operators. Intervention strategy may include (1) improving the worker's signal-detection response with positive feedback; (2) improving the usefulness of signal detection through the use of narrow beam signals; or (3) providing drivers and operators with systems to immediately detect obstructions in the path of intended movement.

Related Field Tests

Several years ago the Bureau of Mines addressed the problem of backup alarms and limited visibilty in open-pit mining operations (Duchon and Laage 1986). Field tests evaluated the use of discriminating backup alarms. Three technologies were evaluated: infrared, ultrasonic, and doppler-radar systems. Alarm systems were configured to flood a detection zone behind the vehicle with infrared light, 50 kHz sound or 10.525 GHz microwaves, depending on the system being tested. Each system was designed to warn the driver/operator of an obstruction in the detection zone, which needed a positive reaction before moving the vehicle in that direction. The depth of the detection zone was targeted at 15–20 ft (4.62–6.16 m), but this could be adjusted by changing the sensitivity of the equipment. Field trials demonstrated that the doppler-radar system experienced the least operational problems.

Present Research

The present research was focused on investigating the changes in vigilance decrement that can be attributed to the use of discriminating personal alarms on construction sites to supplement or replace conventional backup alarm systems. Personal alarms triggered by a low-powered, directional transmitter on each vehicle require the worker to actively respond to the alarm by pressing an acknowledgement button. The transmitter signal will only flood the area behind the vehicle, when it is reverse gear, and will extend only to a short distance. Alarm activation will clearly indicate that a vehicle is reversing into the work area of the worker with the activated alarm. An active response on the part of the worker ensures timely reaction; it is also a reminder that they are working in the movement pattern of a vehicle. It if can be shown that workers respond more quickly to personal alarms as compared with conventional alarms, the accident incidence rate could be significantly reduced. Workers are expected to receive immediate reinforcement from a positive reaction to the alarm, which will enable them to quickly identify a vehicle approaching their work space. Signals from personal alarms cannot be ignored or filtered out; the worker is the only one able to silence the alarm.

EXPERIMENT

Subjects

Twelve subjects from a pool of young adults in the age group of 20–25 yr, with no hearing deficiencies, performed the experiment. Subjects were volunteers interested in reducing hazards in the construction industry.

Apparatus/Stimulus

The tests were conducted in the laboratory using recorded sound from local construction projects, played through two separated speakers, as the primary-noise source. One feature of the background noise was the approach and retreat of

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equipment sounds in a doppler-like effect. Several conventional backup alarms at different pitches and intensities were included in the background noise. During the field recording sessions, three operations were under way. Large dump trucks were backing onto the building site. Some had no alarms, but added engine noise and the distinctive banging of the tailgate to the general noise level. A tractor with a blade, using a back-and-forth motion, was moving and spreading fill material. In proximity, a vibrating compactor was also operating in areas leveled by the tractor. The tractor and compactor had backup alarms that could be identified on the recording. The equipment operated within 6–8 ft (1.848–2.464 m) of the microphone, or about as close as any worker should get to the equipment. At its closest point, the compactor vibrated a large area, including the microphone stand. During the recording period, an inspector checked the fill for compaction, spotters directed the dump trucks to several dump sites, and other personnel walked in the general area. The sound level of the background construction noise was set at 80 dBA using a sound meter. Spikes of sound from some alarms, etc., exceeded 90 dBA.

Target Alarms

Conventional

An electronic backup alarm (ECCO model 510, 97 dBA) was used to superimpose a conventional target alarm signal on the background noise. The signal was activated in a random pattern during the test period. The alarm was mounted in a baffled box to limit the intensity to a level comparable with alarms on the background noise. The box was located about 10 ft (3.08 m) from the primary-noise source.

Personal

Motorola beepers, furnished by Dial Page Corp., Greenville, S.C., were used to simulate the personal alarms. Each subject was given a beeper to use as a personal alarm. Beepers were programmed to respond to a single telephone number. The signal was activated in a random pattern during the test period. Backup and personal alarms were similar in their signal patterns and intensity and, therefore, were considered comparable.

Primary Tasks

During the experiment, the subject's primary task was that of sorting, which required focused attention. This type of attention is similar to that required by construction workers performing assigned tasks. They must focus most of their attention on their primary task and monitor background noise for warning signals. The sorting task was based on a unique set of sorting cards containing four information fields that can be sorted in ascending or descending order. One information field was the Latin botanical name for a plant, the second field was the common name for the same plant, the third was a six-digit random number, and the fourth field was a nine-digit alphanumeric. Plant names were taken from Stearn (1992); numbers were based on a random number table. Each subject was given four sets of cards to be sorted in the following order during the four phases: common names, Latin names, numeric, and alphanumeric.

Timing System

The timing system consisted of shielded electric lights triggered by the same power switch used to control the conventional target alarm, stop watches, and monitors. Stop watches calibrated in hundreds of a minute were used to measure the response time. During the personal alarm testing phase, monitors were given beepers identical to those used by the subjects to identify initiation of the alarm.

Procedure

The experiment required the subjects to perform their primary tasks and detect the target alarms while being exposed to construction noise from the primary-noise source. The design of the experiment is shown in Table 2. Counterbalancing was used to control operator variability and to account for operator fatigue. In all there were 12 subjects. Six subjects performed the test first using the conventional alarm and later the personal alarms. The remaining six subjects performed the test first with personal alarms and later with conventional alarms. The subjects were randomly assigned to either of the two counterbalanced conditions. The experiment was designed to limit the number of possible sources for the expected decrement. For example, the timing of alarms during the conditioning phase was very similar to the timing during the test phase to avoid possible decrement resulting from differences in event timing (Craig 1978). The primary-noise source and target conventional alarm were located near the front of the room. Speakers on the primary-noise source were separated by at least 6 ft (1.48 m) and were arranged to fill the room with nondirectional background noise. The target conventional alarm was located about 10 ft (3.08 m) from the nearest speaker. Subjects were arranged parallel to the sound components and approximately 6 ft (1.048 m) apart. A monitor was located behind each subject to measure the time lapse between signal initiation and detection.

Phase I: During this phase subjects were exposed to normal construction-equipment operating noise with varying tones and intensities of conventional backup alarms for a period of 20 min. Subjects were asked to respond to a signal whenever they recognized the target backup alarm. Reaction response was measured from alarm initiation to response to each alarm. This phase was intended to condition the subjects to the type and level of construction noise, provide time for them to learn to discriminate the target alarm signals from background noise, and to develop a statistical foundation for follow-on phases of the tests. Subjects performed the first sorting of card during this conditioning period.

Phase II: The second phase, which lasted for 20 min, was similar to the first and used the same background noise and target alarm. The second sorting of the cards was accomplished. Following the completion of this phase, subjects were given a 10-min rest.

Phase III: In the third phase subjects repeated the 20-min conditioning phase to become accustomed to the background noise and target alarm again. The third sorting of the cards was accomplished during this phase.

Phase IV: In the fourth phase, subjects received individual alarms on the beepers acting as personal alarms. This phase covered a 20-min period. The fourth sorting of the cards was accomplished during this phase.

The second group of subjects used a similar four-phase process, with phases II and IV reversed as shown in Table 2.

TABLE 2. Test Procedures

Phase (1)	Subjects 1–6 (2)	Subjects 7–12 (3)
I	Conditioning	Conditioning
II	Conventional alarm	Personal alarm
Rest period	Rest	Rest
III	Conditioning	Conditioning
IV	Personal alarm	Conventional alarm

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Data Collection

Data were collected during the second and fourth phases, from the time of initiation of the signal to the time for the subjects to respond. Data were recorded for the first 5 min and the last 5-min intervals of each phase. Data were also collected on the number of incorrect responses made by the subjects during the primary sorting tasks. A paired comparison t-test was used to determine any significant differences in performance time and the number of errors made on the primary task.

RESULTS

Experimental results indicate that subjects responded more rapidly to the personal alarms (active response) than to the conventional alarms (passive response). (Refer to Table 3 for overall mean response times for conventional and personal alarms). The time required to respond to personal alarms was significantly lower than that required to respond to conventional alarms (t = 1.834, $p < 0.05$), Fig. 1. The largest differences occurred during the last five alarms during each test phase (t = 2.156, $p < 0.05$), as shown in Fig. 2. Fig. 3 shows that a significant increase in response time was experienced between the first five and the last five alarm responses (t = 2.016, $p < 0.05$) for the conventional alarm, and that there was a decrease in response time (t = 2.580, $p < 0.05$) for the personal alarm. Thus, the subjects required less time to respond to personal alarms than to conventional alarms. The average response time for the personal alarm in the first interval of five alarms is considered conservative because some of the subjects initially experienced difficulty in identifying the alarm; subjects were not conditioned to the alarm before performing the data-collection phase.

TABLE 3. Mean Times for Alarm Systems

Subject number (1)	Beeper alarm overall means (sec) (2)	Conventional alarm overall means (sec) (3)
1	1.500	1.800
2	1.125	1.308
3	2.083	1.154
4	1.417	2.733
5	2.402	1.633
6	1.909	1.944
7	1.083	1.533
8	1.455	2.059
9	1.727	1.059
10	1.272	2.500
11	1.272	2.733
12	1.535	1.859

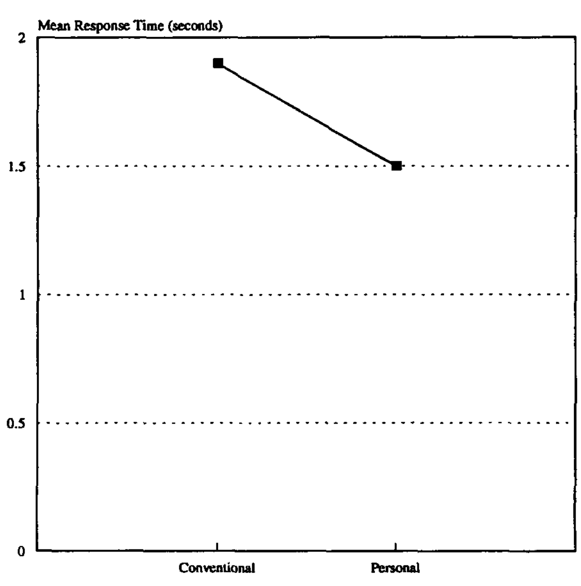

FIG. 1. Average Response Time for 12 Subjects (First 5 min)

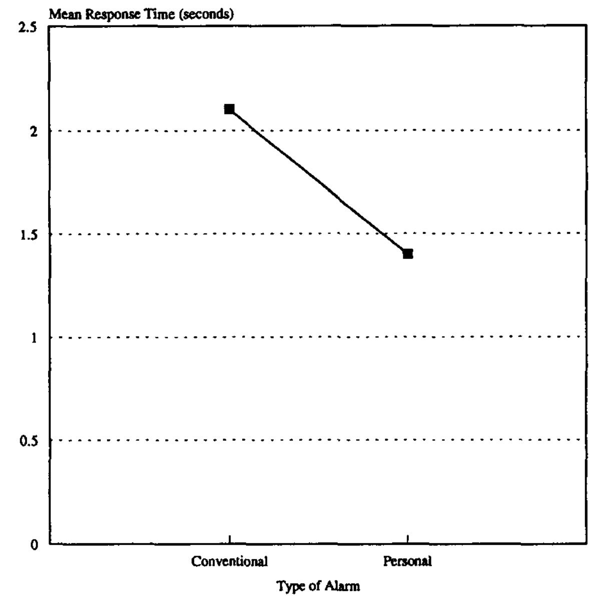

FIG. 2. Average Response Time for 12 Subjects (Last 5 min)

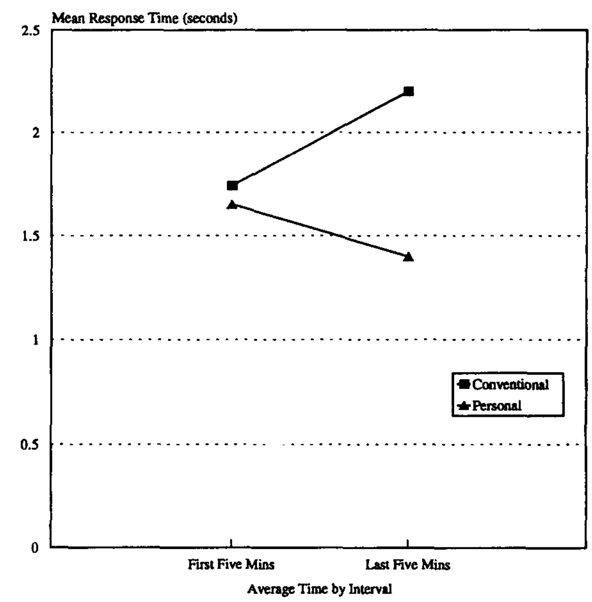

FIG. 3. Average Response Time for 12 Subjects (Both)

ANALYSIS

Subjects responded more quickly to personal alarms requiring positive feedback as compared with conventional backup alarms. Because of this positive-feedback reaction, subjects did not experience a vigilance decrement when using the personal alarms.

Safety problems related to backup alarms are caused by vigilance decrement; a basic human characteristic that people cannot sustain attention on an object over a long period of time. The reasons construction workers experience a decrement in vigilance for backup alarms has been experimentally demonstrated to confirm the Treisman (1969) model. The construction worker's normal work environment generally

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contains at least two auditory channels plus a visual channel on their primary tasks. This situation was modeled for the experiment and the results confirmed the expected outcome.

In the experiment the primary-noise source was separated by 10 ft (3.08 m) or by more than a degree visual angle for any subject, forming two separate auditory channels. The use of two auditory channels plus a visual task appears to simulate normal working conditions for constructon workers subjected to the hazards of maneuvering trucks and mobile equipment. The first channel is the aforementioned construction background noise, which included several conventional backup alarms. The target conventional alarm creates the second channel of information simulating a vehicle operating in the worker's area. The worker's primary task is the visual channel. Workers experience a three-way competition for their mental resources, which over time results in mental fatigue. Workers tend to assign more mental resources to their primary task and much less attention to monitoring the two auditory channels of communication.

An increase in the decrement was experienced as the subjects reacted to the conventional alarm. This increase indicates the effects of mental fatigue from serially processing two channels of information while concentrating on the primary task.

During the personal-alarm test phase, a single channel of communication was established with the background noise and the personal alarm. By placing the personal alarm on the worker, its signal was automatically combined with the one auditory channel (background noise). Subjects were able to efficiently process the information in the single channel in parallel. Even though the two auditory signals had independent implications, the information was processed in parallel.

Vigilance decrement was experienced with the conventional alarm even though (1) the background noise contained an example of the conventional alarm that simplified the comparison of sounds and detection of the target alarm; (2) the frequency of alarms during the conditioning phase was equivalent to that used during the test, so subjects were not exposed to changes in alarm timing or patterns; and (3) the alarm was sounded frequently during the test period, which should have helped the subjects maintain a high arousal rate and quick response time.

The increase in sensitivity in the response to the personal alarm appears to reflect the effects of a learning curve. Subjects were not conditioned to the personal alarms before the test. A short introduction to the personal alarm was given just before the test. The conditioning period preceding the test period was used to condition subjects to the background noise.

CONCLUSIONS

Safe behavior can be encouraged by requiring positive feedback on warning alarms. The number of injuries and fatalities could be significantly reduced by encouraging and reinforcing this behavioral change. This study confirms the findings of other researchers that positive feedback will encourage safer behavior.

Experimental results indicated that the decrement in vigilance can be significantly reduced by a better understanding of how the mind works and how human memory performs. Building on the channels of communication research, it was found that workers will respond more consistently and quickly to a personal alarm (a single communication channel), than to conventional backup alarms (requiring two channels). The current backup warning alarm system does not include a positive reaction or feedback for the construction worker or the driver/operator. Without either of these positive reactions, workers try to be aware of their surroundings, but allocate an increasing amount of their mental capacity to their primary tasks. Signals can easily become habituated or misinterpreted, which often results in injuries or fatalities.

Use of the personal alarm combines the warning signal into the same channel as that of the background noise. The signal can be detected with little distraction from the primary task. Positive reaction to each alarm appears to increase the level of vigilance. It is anticipated that, on the jobsite, workers will also receive positive feedback knowing each alarm indicates a vehicle is moving toward their work area, further encouraging changes in behavior. Because the reason for each alarm can easily be confirmed by the workers, the feedback reinforces safe behavior on the site. Over a short period, it was shown that response times decrease as workers become accustomed to the alarm.

During the test period, the data indicated that response to conventional alarms increased with the worker's need to concentrate on his or her primary tasks, increasing fatigue from monitoring two communication channels, and the loss of the alarm as it blends into the background noise.

The Bureau of Mines field tests demonstrated that discriminating alarms are effective in avoiding accidents while reversing a vehicle. The discriminating alarm system provides positive feedback to the driver and requires a positive reaction before the vehicle can be safely moved. Discriminating alarms can be focused to detect obstructions within 20 ft (6.16 m) of the back of the truck; the alarm cannot be silenced until the truck moves out of the reverse gear or till the obstruction is removed. However, without spotters, drivers must stop the truck, dismount, and find the obstruction. Personal alarms would be more effective when used in conjunction with the discriminating alarms. Used together, both drivers and workers on the ground receive warning signals that require a positive feedback. Workers could use the warning signals to help drivers safely maneuver their vehicles.

Based on the results of this research, the following actions should be taken in cooperation with a construction contractor.

Performance specifications should be prepared for the discriminating personal alarms and transmitters. A limited number of alarms and transmitters should be produced for use in field testing. Representative samples of doppler and ultrasonic discriminating alarm systems should also be acquired.

A field-test program should be developed for the warning systems. Field tests should be conducted on a building site that requires a substantial amount of earthwork. Performance tests should be made using various combinations of the personal and discriminating alarms. Waivers should be obtained to eliminate conventional alarm systems during the test period.

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