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DESIGN AND IMPLEMENTATION OF EARTHQUAKE EARLY WARNING SYSTEMS IN TAIWAN

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ABSTRACT

Two prototype earthquake early warning systems have been implemented in Taiwan: (1) an alert system exploring the use of modern technology to cover the highly seismic area of Hualien, and (2) a rapid response system using a telemetered network of digital accelerographs to cover the entire island. These systems are designed to provide critical information that may aid in reducing loss of property and lives, in directing rescue operations, and in preparing for recovery from earthquake damage. Both systems are exploratory in nature, and we hope that the experience we gained can be quickly utilized for implementing earthquake warning systems for specific missions.

KEYWORDS

Accelerographs, earthquake early warning, earthquake rapid response, seismic alert, Taiwan.

INTRODUCTION

After nearly 30 years of earthquake prediction research, the ability to predict the time, place, and magnitude of an earthquake accurately for practical use remains elusive (Geller, 1991; U. S. National Research Council, 1991). However, present technology in seismic instrumentation and telecommunications permits the implementation of a system for earthquake early warning. Such a system is capable of providing from a few seconds to a few tens of seconds of warning before the arrival of strong ground shaking caused by a large earthquake. Such timely information is essential to minimize damage and loss of lives in metropolitan areas.

The idea of an earthquake early warning system for San Francisco was proposed more than one hundred years ago by Cooper (1868). A modern approach for a seismic computerized alert network was published by Heaton (1985). For more than twenty years, Japan has benefited from an earthquake warning system on their "bullet" trains (Nakamura and Tucker, 1988), and an intelligent earthquake warning system called UrEDAS is being implemented in Japan (Nakamura, 1988; 1995; 1996). A seismic alert system has been implemented in Mexico City (Espinosa-Aranda *et al.*, 1995a), and successfully provided about 70 seconds of advanced warning of the September 14, 1995, Copala (Guerrero, Mexico) earthquake (about 300 km away) to the citizens of Mexico City (Espinosa-Aranda *et al.*, 1995b; 1996).

Implementing earthquake monitoring systems with warning capability for Taiwan was proposed by W. H. K. Lee and T. L. Teng to the Central Weather Bureau (CWB) of Taiwan in December, 1990, and was funded in 1992. In order to facilitate the development of earthquake warning systems in Taiwan, a cooperative development program between the CWB and the U.S. Geological Survey (USGS) began in July, 1992, and was completed in June, 1995 (Lee, 1993; 1994a; 1995). A similar cooperative program between the CWB and the Southern California Earthquake Center (SCEC) also began in July, 1992, and has continued to the present (Teng *et al.*, 1994; 1995).

BENEFITS OF AN EARTHQUAKE WARNING SYSTEM

An earthquake early warning system has the potential for the quickest return of benefit to society. Such a system can provide the critical information needed (1) to minimize loss of property and lives, (2) to direct rescue operations, and (3) to prepare for recovery from earthquake damage.

The most effective use of earthquake early warning is to activate automated systems to prepare for incoming strong ground shaking. For example: slowing down rapid-transit vehicles and high-speed trains to avoid potential derailment, orderly shutdown of pipelines and gas lines to minimize fire hazards, controlled shutdown of manufacturing operations to decrease potential loss, and safe-guarding computer information by saving vital information and retracting disk heads away from the disk surface. All the above can be accomplished to a useful extent within several seconds of notification time.

Although human response may take more than a few seconds, personal safety can be greatly enhanced if several seconds of notification is available: school children can seek cover under desks and workers can move away from hazardous positions. More important, early earthquake notification will greatly reduce panic and confusion. The functions of a modern society, including civil and military operations, will be less likely to turn into chaos if an early earthquake notification is available and drills for appropriate actions have been performed. For example, the Mexico City Alert System (and associated programs to educate the public) has demonstrated its usefulness on the September 14, 1995 earthquake (Espinosa-Aranda *et al.*, 1995b; 1996).

With an earthquake early warning system, we can estimate quickly the maximum expected ground motion caused by an earthquake so that emergency response teams can be deployed where they are needed most. Because such a system monitors earthquakes in real time, information on the earthquake sequence (main shock and aftershocks) will be readily available while the events are in progress.

DESIGN CONSIDERATIONS

The physical principle of an earthquake early warning system is simple: strong ground shaking is caused by shear (S) and the following surface waves which travel at about half the speed of the primary (P) waves, and seismic waves travel much slower than electromagnetic signals transmitted by telephone or radio. For example, Fig. 1c shows a plot of travel time for P-wave and S-wave versus distance using the following assumptions of a destructive earthquake: (1) focal depth at 20 km, (2) P-wave velocity at 6 km/sec, and (3) S-wave velocity at 3.5 km/sec.

If an earthquake is located at 100 km away from a city, the P-wave arrives in the city at about 17 seconds, and S-waves at about 29 seconds (see Fig. 1c). If we deploy a dense seismic network in the earthquake source area that is capable of locating and determining the size of the event in about 10 seconds, then we will have about 5 seconds to issue a warning before the P-wave arrives, and about 17 seconds before the more destructive S-waves and surface waves arrive at the city. Here, we have assumed that it takes very little time (say, about 2 seconds) to send a signal from a seismic network to the city.

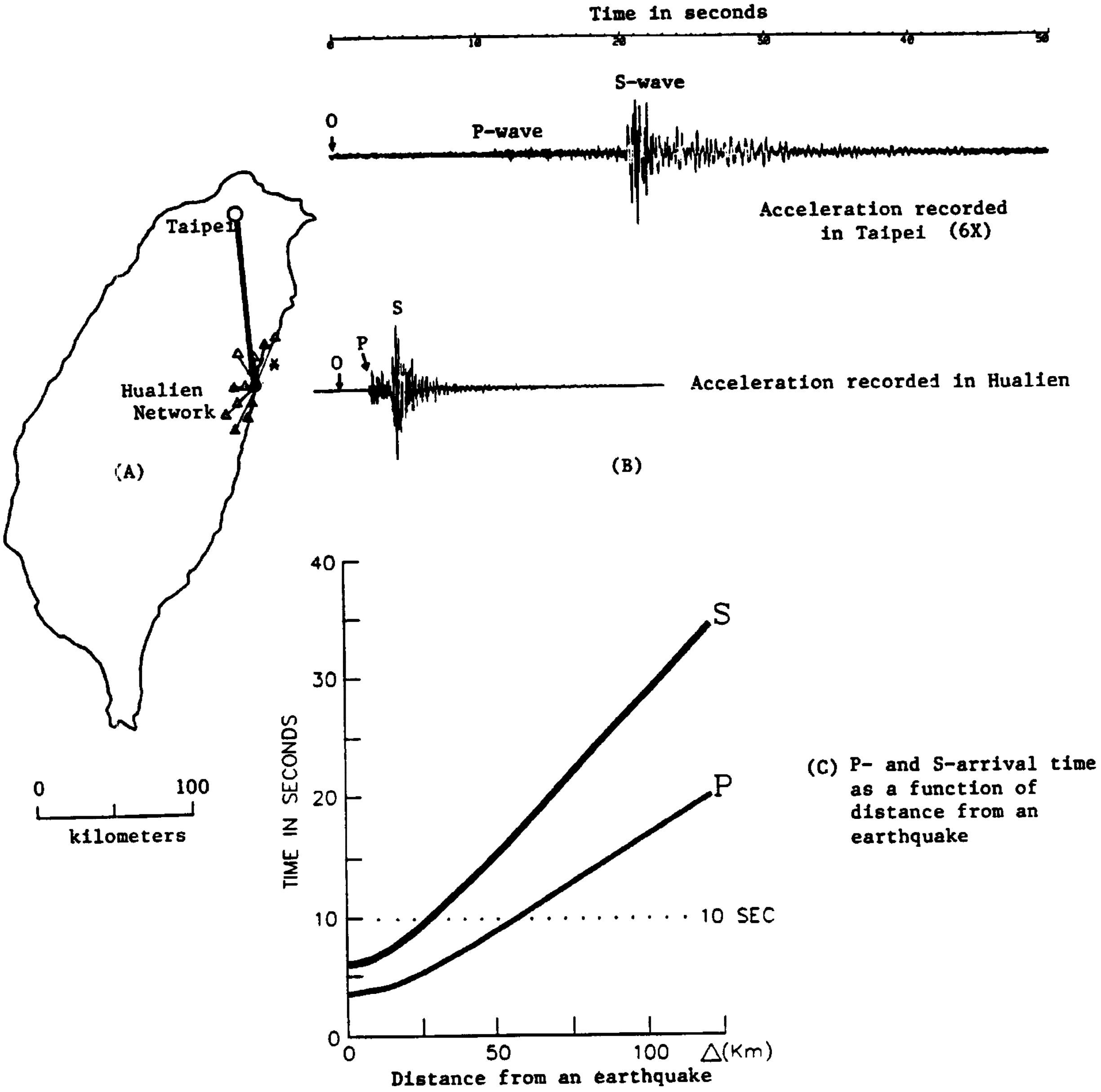

Fig. 1. A prototype earthquake early warning system in Taiwan (see text for explanation).

From Fig. 1c, it is clear that the above strategy may work for earthquakes located about 60 km or more away from a city. For earthquakes at shorter distances (say, 20 to 60 km), we must reduce the time for detecting the event and issuing an warning to about 5 seconds. For earthquakes within 20 km of a city, there is little one can do other than installing automatic shut-off devices that can be triggered by the onset of the P-wave.

For the Taipei metropolitan area, the most likely destructive earthquakes may be those located in the Ilan and Hualien areas (at distances of about 30 to 120 km). Therefore, any earthquake warning system must be able to locate an earthquake and determine its size within 10 seconds after it occurs. Fig. 1A illustrates the situation for Hualien with a sample earthquake recorded both at Hualien and in Taipei (Fig. 1B).

In the above discussion, we have a basic assumption in mind, i.e., in order for the issuance of earthquake early warning to be practically worthwhile in Taiwan, the earthquake must have a magnitude of $M \geq 7$ at distance of 50 km away, and $M \geq 8$ at distance of 100 km away. There are exceptions, such as the Mexico City case where large earthquakes at 300 km or more away can do damage. In the Taiwan case, an empirical relationship that gives the practicality of an earthquake early warning may be:

$$M = 4\ log\Delta\ \ (km)$$

where M being the magnitude, and Δ being the approximate epicentral distance in kilometers. Obviously, even great earthquakes at large distance will have inconsequential impact to a city in Taiwan. Furthermore, the empirical relationship:

$$M = 6.1 + 0.7\ logL\ \ (km)$$

relates magnitude M to the approximate length of fault rupture L. At a rupture velocity of 2.5 km/sec, we can construct the following table that relates the magnitude M, the maximum distance of consequences Δ(km), the estimated rupture length L(km), and the rupture duration τ(sec) as follows:

M	Δ(km)	L(km)	τ(sec)
7.0	50	20	8
7.5	75	100	40
8.0	100	500	200

From this table, in view of L and τ, there is no practical need to know the earthquake hypocenter to better than ±10 km, and origin time to better than ±1 sec. In fact, the picking of P-and S- arrivals is not important, nor is it needed to go through the standard travel time inversion to locate the earthquake. For practical earthquake early warning, the "epicenter" may be defined to be the location of maximum peak ground acceleration (PGA), and "origin time" to be the moment when the maximum PGA occurs. The crucial problem is to determine the magnitude to within ±0.3 magnitude unit in as short a time as possible.

A practical way to determine the magnitude is to estimate the fault rupture length. If a number of stations spanning a region of 20 km all give a PGA of 0.5g or higher, we may define the magnitude to be 7 or larger. Since the requirement of early warning imposes the condition that the earthquake parameters be determined within a few seconds, these parameters must have "transient" values and should be updated as the rupture is developing, so that new "epicenter", "origin time", and "magnitude" will appear. If a later and higher PGA occurs, it will have similar propagation delay time before it reaches the metropolitan area. So, in the sense of early warning with a propagating rupture, only the outputs of a number of strategically placed strong-motion stations are monitored. As the rupture develops, "epicenter" and "origin time" are updated, and the "magnitude" is revised upward to correspond to the higher value of PGA, or the larger rupture length. This entire process is very similar to the hurricane warning that reports the progress of evolution of the "eye" of the hurricane and its extent, which have been found to be useful to society.

IMPLEMENTATION CONSIDERATIONS

Although telemetered seismic networks have been in existence for a few decades (see e.g., Lee and Stewart, 1981), it usually takes a few minutes before the data are processed and an estimate of earthquake location and magnitude are issued. In addition, most telemetered seismic networks use short-period seismometers and the signals are "clipped" for strong earthquakes. Fortunately, a strong-motion instrumentation program in Taiwan (to install an equivalent of 1,000 three-component digital accelerographs) began in 1991. During the instrument acquisition, we are able to specify accelerographs capable of digital stream output so that they can be easily integrated into the existing telemetered seismic network.

In implementing the prototype earthquake early warning systems in Taiwan, we explore two approaches: (1) a dense telemetered accelerograph network (covering a very small area) with realtime data processing and communication, and (2) expand the existing regional telemetered seismic network (covering the entire Taiwan) with modern accelerographs and realtime data processing and communication. In both cases, we make use of existing commercial hardware and the published IASPEI software (Lee, 1994b; 1994c) to minimize development cost.

A PROTOTYPE EARTHQUAKE EARLY WARNING SYSTEM IN HUALIEN

The primary objective for this prototype system in Hualien is to explore the use of modern technology for earthquake early warning purposes. This prototype system consists of three parts:

Realtime Seismic Monitoring Network

The equipment of this realtime seismic monitoring network was supplied by Nanometrics in April, 1994, and has operated successfully according to specifications. However, fine-tuning and integration with other supporting systems are still in progress. It consists of 12 remote three-component accelerometers telemetered digitally via 9600-baud telephone lines to the CWB Hualien Station. At the Hualien Station, the incoming digital signals are processed in real time and the results are telemetered to the CWB Headquarters in Taipei for control and display (Chung *et al.*, 1995).

Realtime Seismic Monitoring Platform

This realtime seismic monitoring platform was developed at the USGS. In this platform, the signals from the Nanometrics' network, digital streams from CWB free-field accelerographs, and digital streams from the Quanterra broad-band stations can be used as input. A PC-based digital data acquisition and processing sub-system (Lee, 1994b; 1994c) performs realtime monitoring of earthquakes and issues earthquake warning messages, which can be sent to CWB Headquarters in Taipei directly or via the Nanometrics network system. The reason for this second system is to provide redundancy and to provide a general platform to try out various scientific algorithms for detecting, locating, and quantifying the earthquakes.

Realtime Broad-Band Station

At the Hualien Station, we also use one of the three realtime broad-band stations delivered by Quanterra under contract in June, 1994. Each broad-band station consists of a STS-2 broadband seismometer made by Streckeisen and a 24-bit digital data acquisition and recording unit with digital data stream output. Earthquake warning messages from a broad-band station can also be sent to CWB Headquarters in Taipei via the Nanometrics' network system and/or via the USGS realtime seismic monitoring platform. The reason for this third system is to provide redundancy in case the telephone telemetry from field stations to the Hualien Station is broken, and to provide high quality broad-band seismic data for post earthquake research studies.

A RAPID RESPONSE SYSTEM USING TELEMETERED ACCELEROGRAPHS

The regional telemetered seismic network (with 75 short-period, 3-component seismic stations) operated by CWB (see Fig. 2) uses only half of the bandwidth of 9600-baud telephone lines for telemetry. As first pointed out by T. L. Teng, the remaining half of the bandwidth of 9600-baud telephone lines can be utilized to telemeter data to CWB Headquarters without any increase in operational costs. With the availability of free-field digital accelerographs with digital data stream output and the USGS realtime seismic monitoring platform, it is possible for CWB to implement a realtime, regional, telemetered strong-motion network in Taiwan with very little additional capital and operational costs.

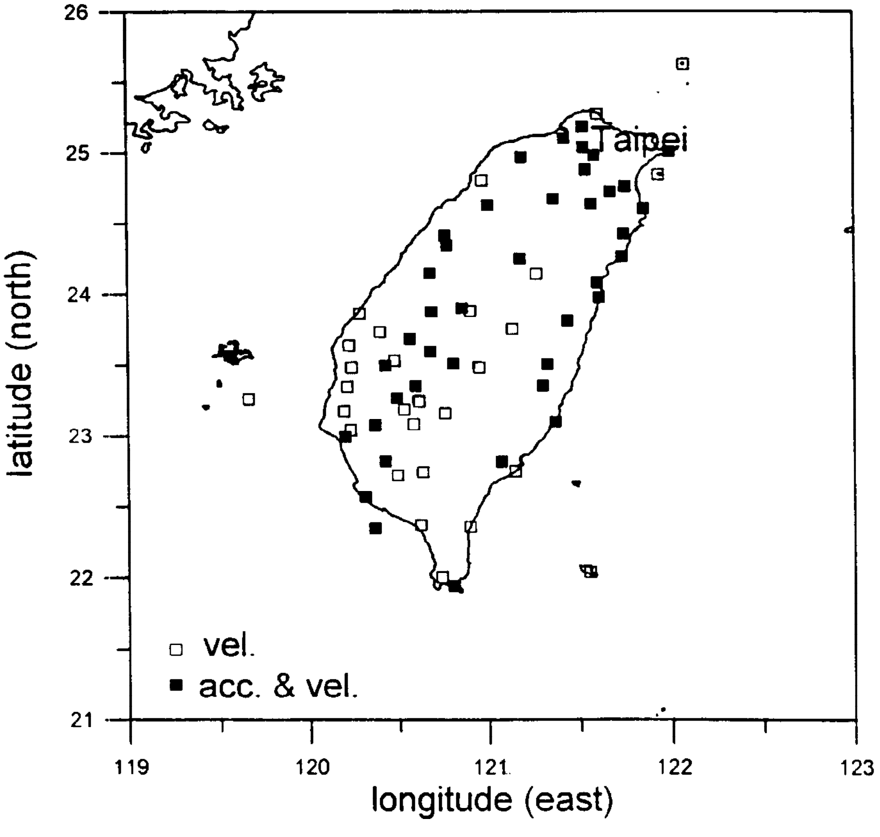

Fig. 2. Map showing station locations of telemetered digital accelerographs and short-period seismographs (solid squares), and of telemetered digital short-period seismographs (open squares) in Taiwan.

DISCUSSION

Part of the successful dissemination and activation of the SAS receivers in Mexico City on September 14, 1995 has been due to the tests which have permitted to maintain a periodic supervision of the radio receivers, assuring that the system was completely functional and offering opportunities for improvements in its operation. Also, the public education, training and drills have permitted an adequate response of part of the public. The best response was from the public schools with a population of children with ages from 5 to 15 years of age, which have the highest level of training and experience.

The system had a cost of $1.2 million dollars for development and installation and $200,000 per year for maintenance. The facts that most major earthquakes which are likely to cause damage in the capital are from the Guerrero coast, the people reached by the early warning in schools and METRO if an earthquake strikes on rush hours is about of 2.5 million persons and 4 million listening radio stations make the Seismic Alert System a low investment with high benefit return social value for the Mexico City population.

As it currently operates, the SAS is relatively simple technically with the need to enhance the instrumentation. Limited in its sensor and warning coverage, it provides warning only for events along the Guerrero coast to the people of Mexico City. Earthquakes with other sources could strike Mexico City without warning as it happened in the M7.5 Colima earthquake of October 9, 1995 and M6.5 Chiapas earthquake of October 20, 1995.

More than 100 applications of institutions and private organizations for new installations of SAS radio receivers have been submitted. Unfortunately the current economic situation in Mexico today is still not favorable for expansion of the early warning system. This demand implies the future expansion of the SAS Radio Warning System for users and CIRES technical infrastructure.

Today the applications to schools, public buildings and its limited deployment in the industry at present has not generated controversy. As further deployment of the system proceeds, the system will be more complex and difficult to maintain with a limited budget. There will be greater social and economic consequences as critical processes and functions are unnecessarily curtailed or disrupted in a false alert or malfunction.

Finally, the problem of warning in an scenario of an earthquake striking at night, where the coverage is low, still remains. It requires the implementation of a low cost dissemination channel that can be activated even if the device is turned off.

CONCLUSION

Although establishing a warning effectiveness factor or measure is somewhat ambiguous, the experience of September 14 demonstrated that the combination of adequate public education, training, drills and a properly issued warning can have high social consequences in case of an earthquake disaster. Residents of seismically vulnerable regions can be expected to respond to a brief warning in a controlled, rational and adaptive manner as was demonstrated by the performance of students in the Mexico City public schools.

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donado (1996). Results of the Mexico City early warning system. *Proc. 11th World Conf. Earthq. Eng.*, this Volume.

Geller, R. J. (1991). Shake-up for earthquake prediction. *Nature, 352*, 275-276.

Heaton, T. H. (1985). A model for a seismic computerized alert network. *Science, 228*, 987-990.

Lee, W. H. K. (1993). A project implementation plan for an advanced earthquake monitoring system. *Research Report of the Central Weather Bureau, Taipei, Taiwan, R.O.C., No. 444*, 89 pp.

Lee, W. H. K. (1994a). A project operation plan for an advanced earthquake monitoring system. *Research Report of the Central Weather Bureau, Taipei, Taiwan, R.O.C., No. 445*, 69 pp.

Lee, W. H. K. (Editor), (1994b). *Realtime Seismic Data Acquisition and Processing. IASPEI Software Library Volume 1, Second Edition*, Seismological Society of America, El Cerrito, CA, 285 pp.

Lee, W. H. K. (Editor), (1994c). "Plotting and Displaying Seismic Data", IASPEI Software Library, Volume 2 (Second Edition) ", Seismological Society of America, El Cerrito, CA, 254 pp.

Lee, W. H. K. (1995). A project implementation plan for an advanced earthquake monitoring system. *Research Report of the Central Weather Bureau, Taipei, Taiwan, R.O.C., No. 448*, 411 pp.

Lee, W. H. K. and S. W. Stewart (1981). *Principles and Applications of Microearthquake Networks*, Academic Press, New York, 293 pp.

Nakamura, Y. (1988). On the Urgent Earthquake Detection and Alarm System (UrEDAS), *Proc. Ninth World Conf. Earthq. Eng.*, *7*, 673-678.

Nakamura, Y. (1995). UrEDAS and HERAS. *IUGG XXI General Assembly, Abstracts Week A*, p. 406.

Nakamura, Y. (1996). Real-time information system for hazards mitigation. *Proc. 11th World Conf. Earthq. Eng.*, this Volume.

Nakamura, Y. and B. E. Tucker (1988). Japan's earthquake warning system: should it be imported to California? *Calif. Geology, 41 (2)*, 33-40.

Shin, T. C., Y. B. Tsai and Y. M. Wu (1996). Rapid response of large earthquake in Taiwan using a realtime telemetered network of digital accelerographs. *Proc. 11th World Conf. Earthq. Eng.*, this Volume.

Teng, T. L., M. Hsu, W. H. K. Lee, Y. B. Tsai, F. T. Wu, Y. T. Yeh and G. Liu (1994). Annual report to the Central Weather Bureau on earthquake early warning system and implementation of the strong motion instrumentation program. *Research Report of the Central Weather Bureau, Taipei, Taiwan, R.O.C., No. 446*, 147 pp.

Teng, T. L., M. Hsu, W. H. K. Lee, Y. B. Tsai, F. T. Wu and G. Liu (1995). Annual report to the Central Weather Bureau on earthquake early warning system and implementation of the strong motion instrumentation program. *Research Report of the Central Weather Bureau, Taipei, Taiwan, R.O.C., No. 449*, 191 pp.

U. S. National Research Council, (1991). "Real-Time Earthquake Monitoring: Early Warning and Rapid Response". National Academy Press, Washington, D.C., 52 pp.