CHAPTER VI

SINGLE-LAYERED RESERVOIR

The purposes of studying the single-layered reservoir case are:

1. to investigate the validity of using the material balance method or the p/z plot for a gas reservoir to estimate GIIP and reserves, and

2. to investigate the effects of various parameters on the calculated GIIP and reserves. However, because the only difference between GIIP and reserves for gas reservoir on the p/z plot is that GIIP is read at $\bar{p} = 0$ while reserves is read at $\bar{p} =$ abandonment pressure, the following investigation will concentrate only on GIIP.

6.1 Evaluation of GIIP

As mentioned before, the value of GIIP can be calculated in three different ways using available data generated in this study. That is, GIIP can be calculated by :

- volumetric method from known values of rock and fluid properties. This task is carried out by the simulator. GIIP calculated this way is considered to be the actual GIIP.
- material balance or p/z plot method using available fluid properties and $\bar{p}$ which is calculated from the gas pseudo-steady state equation. This way of calculation of GIIP can be carried out in practice. That is, this GIIP value will be the value that one obtains when using available field data.

- material balance or p/z plot method using available fluid properties and $\bar{p}$ obtained from the reservoir simulator. These $\bar{p}$ values (obtained from the reservoir simulator), is assumed to be real values of average reservoir pressure and cannot be obtained in practice.

The three values of GIIP are very useful in investigating the validity of the material balance or p/z plot method and the validity of the value of GIIP obtained in practice. As mentioned above, GIIP obtained by the third method is the GIIP value from the actual $\bar{p}$ of the reservoir which is assumed to be known. Therefore, if the material balance or p/z plot method is the correct method for calculating GIIP, the value of GIIP obtained by the third method must be equal to the GIIP value obtained by the first method. Discrepancy of the GIIP value of the third method (to be called "the material-balance GIIP") from the GIIP value of the first method (to be called "the actual GIIP") reflects the degree of validity of the material balance or p/z plot method. On the other hand, in practice, one does not know the true value of $\bar{p}$ of a reservoir and has to estimate by one of several available methods. Calculation of $\bar{p}$ from the pseudo-steady state equation is one of these methods. That is, GIIP obtained by the second method is the GIIP value which is obtained in practice. Discrepancy of the GIIP value of the second method (to be called "the practical GIIP") from the GIIP value of the first method (or the actual GIIP) reflects the degree of validity of the practical GIIP.

Figure 6-1 shows all three GIIP values mentioned above. It can be seen that the material-balance GIIP and the practical GIIP are only 2.1 % and 4.9 % differences from the actual GIIP, respectively. This should be considered acceptable for all

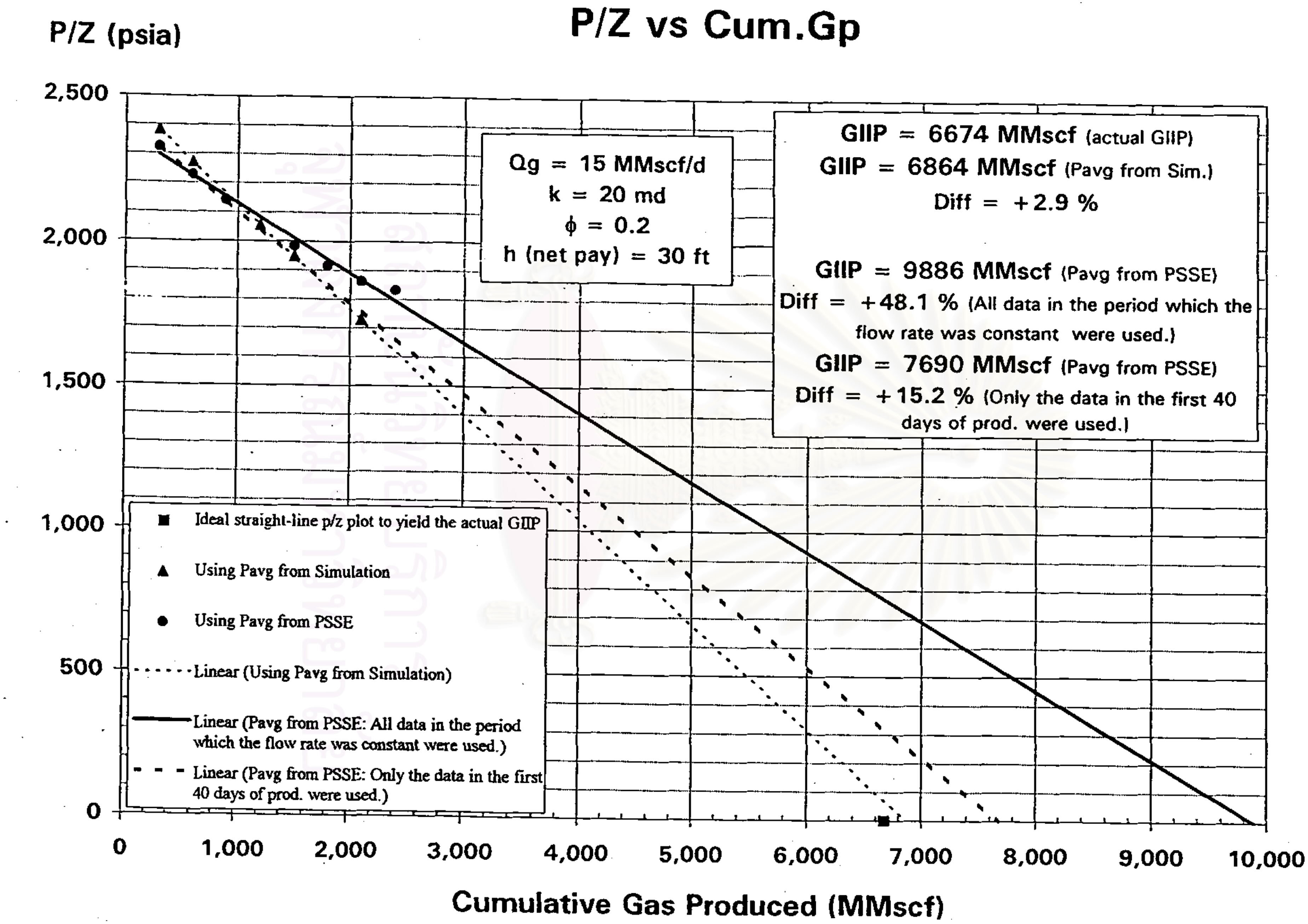

Figure 6-1 The p/z plot for the case with q_g = 5 MMscf/d, k = 20 md

purposes (of using GIIP). However, when one takes a closer look at the data points of p/z plot for evaluating the material-balance GIIP and the practical GIIP, he can see that all the data points for the material-balance case (solid triangles in Figure 6-1) fall on the same straight line while the data points for the practical case (solid circles in Figure 6-1) do not form a straight line and seem to have the concave-upward curve. Therefore, to fit the data points for the practical case, many straight lines are suitable candidates. For example, if only data points (of the practical case) for early time period are used, the straight line will give a practical GIIP very close to the actual GIIP. Therefore, caution should be exercised when drawing a straight line through the data points of the practical case.

Because of the curved shape formed by the data points of the practical case, one may doubt if the pseudo-steady state equation is valid in calculating $\bar{p}$. In this study, when the pseudo-steady state equation is used, all conditions were checked to make certain that they are compliant with the applicability of the pseudo-steady state equation. For example, in Figure 6-1 and the following figures in this study, the pseudo-steady state equation was used only when the gas rate was constant or could be assumed to be constant. In addition, well flowing pressures (p_{wf}) used in the pseudo-steady state equation were obtained from the simulator, hence could be considered as actual values. However, it should be noticed at this point that in practice, one usually does not know the value of p_{wf} but, if necessary, can calculate p_{wf} if the surface pressure and well fluid properties and conditions are known. With this way of calculating p_{wf}, its value may be much different from the actual value.

Nevertheless, judging from the current practices in petroleum industry, there is practically no average reservoir pressure available from well test data for production wells. Hence, use of p_{wf} for calculation of $\bar{p}$ is probably unavoidable in several cases. Therefore, though use of the pseudo-steady state equation to calculate $\bar{p}$ for p/z plot may give incorrect value of GIIP, it is still possible and very useful in giving GIIP value that is close to the actual value if drawing of a straight line on p/z plot is carried out carefully and suitably. From various plots of p/z vs. Gp generated in this study , it is observed that when only data points in the early time period are used for drawing a straight line for the case that $\bar{p}$ is calculated using the pseudo-steady state equation or the practical case, the resulting GIIP will be close to the actual GIIP. It is then recommended that this is done in practice.

Another point worth to be noticed is that for the material-balance case or the case that $\bar{p}$ is obtained from the simulator and considered to be the actual $\bar{p}$ value, the data points fall on the same straight line, as mentioned before. This implies that the change of natural gas in the reservoir is accordant with the prediction of the material balance equation. However, considering the material balance GIIP and the actual GIIP, one sees that they are slightly different. Does this mean that the data points for the material-balance case obey the material balance equation only on the part that they fall on the same straight line, but fail to give the correct value of GIIP ? In an investigation to answer the above question, it was observed that the differences of the material- balance GIIP values and the actual GIIP values for all cases run in this study were very small- less than 3.5 %- and the material-balance GIIP values are always higher. Therefore, it was suspected that the material-balance GIIP values should, in fact, be equal to the actual GIIP values for all cases. The discrepancy may be because of inconsistence of some parameters used. It was later realized that inconsistent use of gas deviation factor, z, may be the cause of the discrepancy. In this study, the actual GIIP values provided by the reservoir simulator were calculated by using the values of z factor from the Redlich-Kwong equation of state[22]. On the other hand, when the p/z plots were prepared, the values of z factor were calculated by using the Dranchuk-Abou-Kassem equation (in the Saphir software). It was later found out that the Redlich-Kwong equation generally gives higher values of z factor than those shown in the Standing-Katz z-factor chart (Silpngarmlers[23], 1998). Because the Dranchuk-Abou-Kassem equation is a very good fitting equation to the z-factor curve in the Standing-Katz chart, it is expected that the Redlich-Kwong equation would also generally give higher values of z factor than those calculated from the Dranchuk-Abou-Kassem equation. Therefore, if the values of z factor calculated from the Redlich-Kwong equation are used in preparation of data points for p/z plots, it is highly possible that the material balance GIIP values would be very close to the actual values. Unfortunately, because detailed calculation could not be carried out during the preparation of this thesis, the conclusion is still speculative. However, it is also expected that even if the material-balance GIIP values calculated using z values from the Redlich-Kwong equation are not exactly equal to the actual values, the differences should be very small, smaller than the differences between the material-balance GIIP values calculated using z values from the Dranchuk-Abou-Kassem equation and the actual values.

If the above discussion is as expected, it can be said that the gas material balance equation or the p/z plot method can be used for all volumetric dry gas reservoirs and the resulting GIIP would be exactly equal to the actual value if correct values of $\bar{p}$ and other parameters are used. Even if the above discussion is not as expected, the gas material balance equation or p/z plot method can still be used for all volumetric dry gas reservoirs, but the only difference is that for this case, the resulting GIIP will be slightly different from the actual value, given that correct values of $\bar{p}$ and other parameters are available. This leads to a very important remark about applicability of the gas material balance equation or the p/z plot method which is based on the tank model to real, complex gas reservoirs. It allows to state that the simple method based on a simplified system can be applied to a real system, given that the required parameters are correct.

Figure 6-1 is a p/z plot for the case when permeability of the gas reservoir is equal to 20 millidarcy (md). It was thought whether higher value of permeability of the gas reservoir, hence gas being able to flow easier in the reservoir, would lead to better results for the p/z plot. This speculation is based on the concept that when gas can flow easier in the reservoir, its behavior should be more closely match to the tank model of the material balance equation. It turns out that this is the case as shown in Figure 6-2. In this figure, three points should be noticed. Both material-balance GIIP and practical GIIP are very close to the actual GIIP. Data points of the material-balance case ($\bar{p}$ obtained from the simulator and considered to be the actual value)

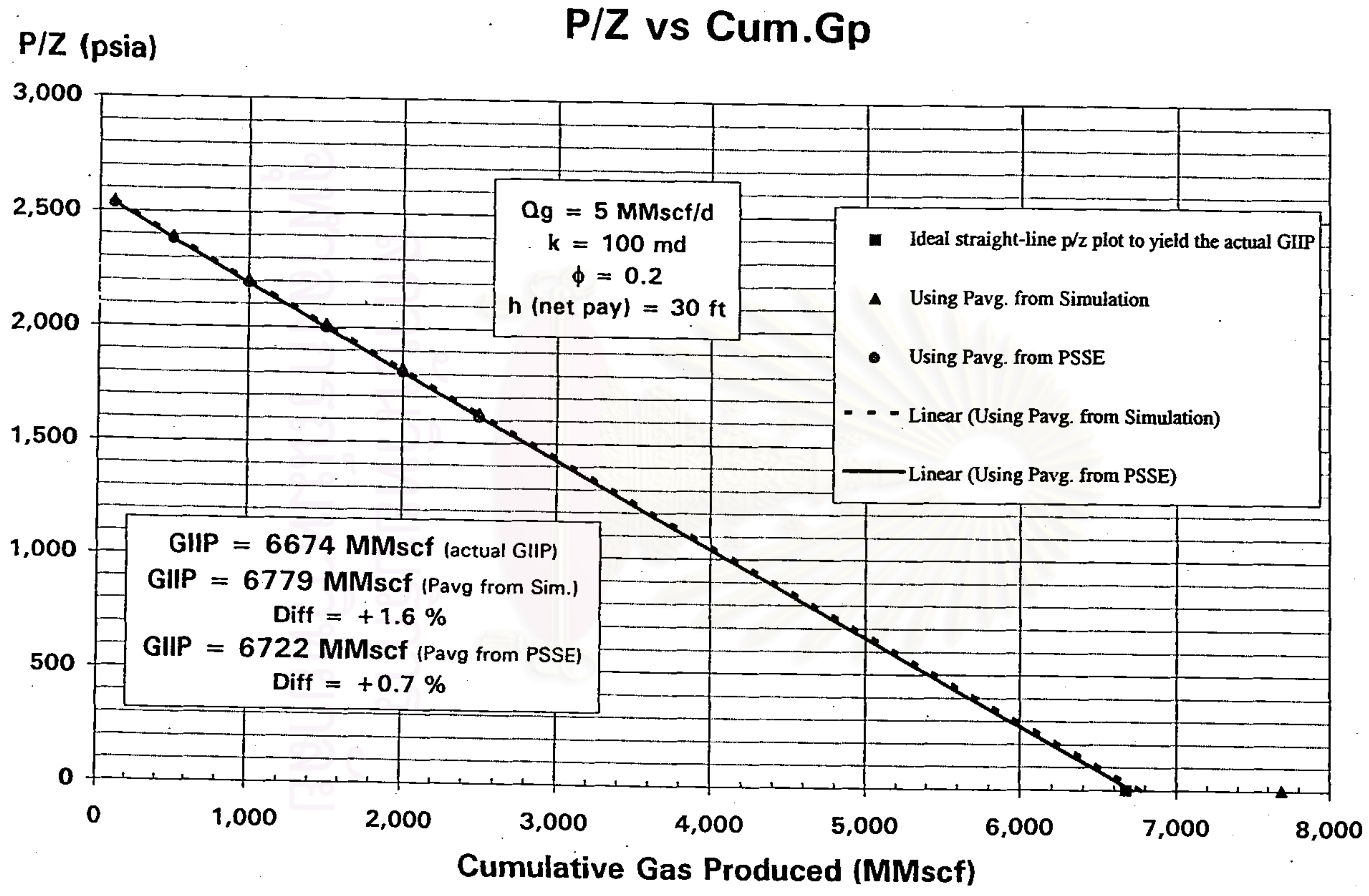

Figure 6-2 The p/z plot for the case of q_g = 5 MMscf/d, k = 100 md

fall on a straight line. Data points of the practical case ($\bar{p}$ obtained from the pseudo-steady state equation) also fall on a straight line and are very close to the data points of the material-balance case. The first remark implies that the material balance equation or the p/z plot method works better for a dry gas reservoir in which gas can flow easier. The second remark is similar to the 10-md case. Therefore, all discussionsthere can be used here. In addition, it should be noticed that the material-balance GIIP for the 100-md case is closer to the actual GIIP than that of the 20-md case. However, because of inconsistence in the use of the z factor, this difference may also be due to that inconsistence.

The significant difference between the 100-md and the 20-md cases are in the third remark. While in the 20-md case, the data points for $\bar{p}$ calculated from the pseudo-steady-state equation are curved, they are on one straight line for the 100-md case. Furthermore, the data points for the 100-md case are very close to the actual values (where $\bar{p}$ obtained from the simulator). This implies that the pseudo-steady state equation works better for the reservoir in which the flow is easier (than that of the 20-md case). This, in turn, leads to the final result that the practical GIIP is very close to the actual GIIP.

The behavior of the data points where $\bar{p}$ obtained from the pseudo-steady state equation for the 100-md case implies a very important point. That is, for a gas reservoir system in which gas can easily flow through, the pseudo-steady state equation and the material balance equation or the p/z plot method can give very accurate values of GIIP, as well as reserves. (The accurate value of reserves is obtained because the straight line drawn through the practical data points almost coincide the straight line drawn through the material-balance data points, Figure 6-2). To further show the effect of easiness or difficulty of gas flow in a gas reservoir on the p/z plot or on the resulting GIIP value, Figure 6-3 is prepared for the case of q_g = 15 MMscf/d and k = 20 md. This figure confirms the previous conclusions as follows:

If the actual value of $\bar{p}$ and gas properties are available, the material- balance equation or the p/z plot method can be used to estimated the actual GIIP very satisfactory. (The material-balance GIIP is very close to the actual GIIP.)

The more difficult the gas can flow through the reservoir (high flow rate, low permeability), the more inaccurate the pseudo-steady state equation can predict $\bar{p}$. Inaccurate $\bar{p}$ values result in deviation of the practical data points from the material-balance data points. This will lead to inaccurate value of the practical GIIP (about 48.1 % different from the actual value in Figure 6-3). It should be noted that inaccurate values of $\bar{p}$ also lead to the curved data points.

If only practical data points for the early period are used in drawing a straight line, the resulting GIIP will be a much better estimate of the actual GIIP. In Figure 6-3, the difference is 15.2 % if only data points in the first 40 days are used, compared to 48.1 % difference if all data points are used.

From Figures 6-1 to 6-3, one can see that in using the material-balance equation or the p/z plot method, several parameters may affect the calculated GIIP

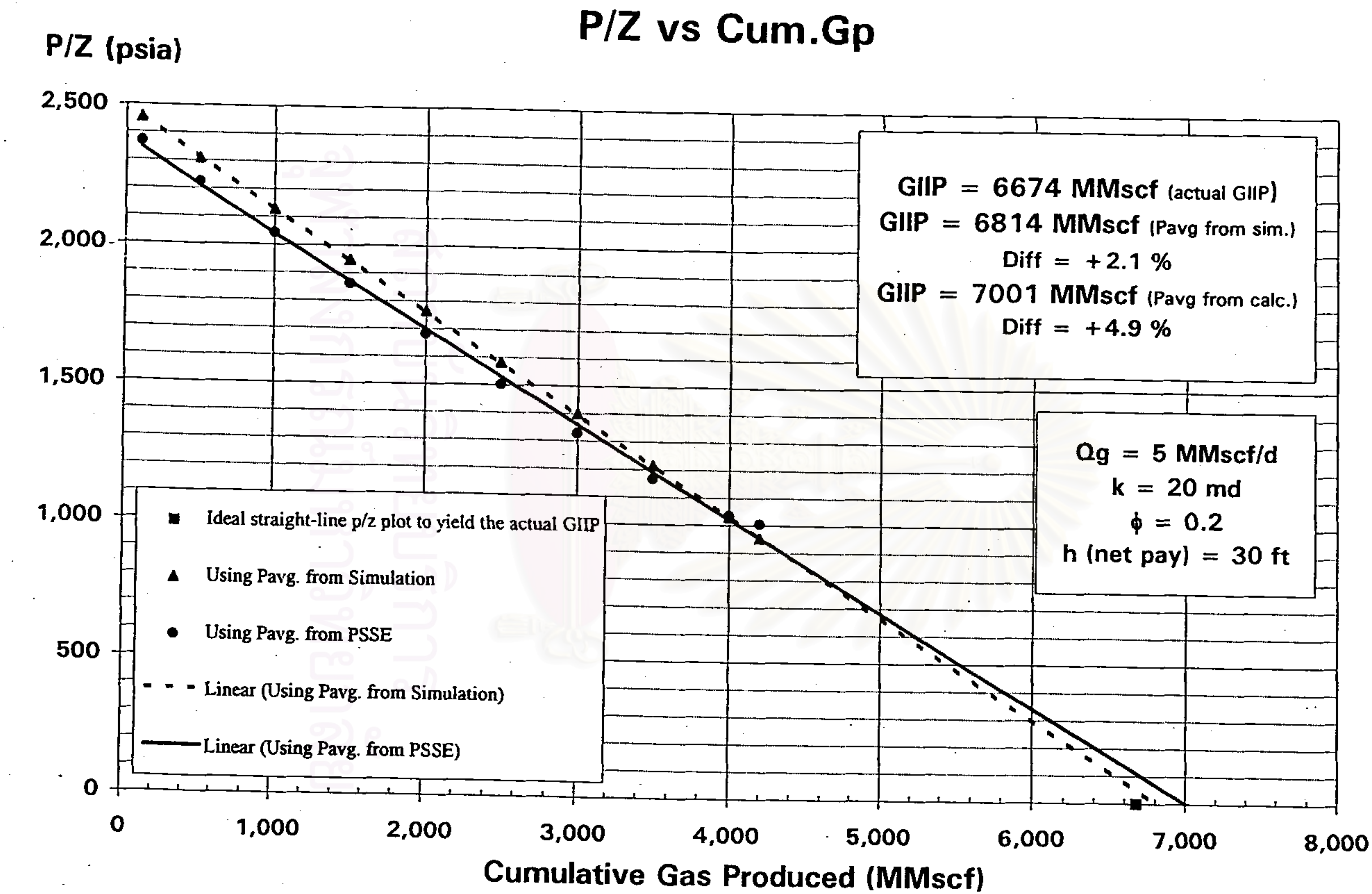

Figure 6-3 The p/z plot for the case with q_g = 15 MMscf/d, k = 20 md

and the shape of the curve on the p/z plot. Therefore, effects of several parameters on the resulting GIIP will be investigated next.

6.2 Effect of permeability

The resulting GIIP values for various permeability values of each gas flow rate are shown in Table 6-1. In the same table, percentage differences of each calculated GIIP values from the actual values are also shown. Before discussing about the effects of permeability on GIIP, its effects on $\bar{p}$ should be investigated.

Figure 6-4 and 6-5 show effects of permeability on $\bar{p}$ at various Gp (or time) for the 5-MMscf/d case and the 15-MMscf/d case, respectively. In these two plots, both the $\bar{p}$ values from the simulation (the actual $\bar{p}$ values) and the $\bar{p}$ values from the pseudo-steady state equation (the practical $\bar{p}$ values) are shown. It is interesting to note that for any value of permeability or gas flow rate, at each Gp, $\bar{p}$ values from the simulator are the same. This is plausible because $\bar{p}$ may be considered as a static quantity, hence not depending on dynamic conditions. Actual $\bar{p}$, then, should not depend on the flow properties but only depend on static fluid properties (assuming that static rock properties are constant). Therefore, when equal volume of gas is withdrawn (Gp), $\bar{p}$ in the reservoir should be the same though flow properties are different. For $\bar{p}$ values calculated from the pseudo-steady state equation at some sufficiently high permeability and sufficiently low flow rate, $\bar{p}$ vales from the pseudo-steady state equation coincide or almost coincide with the actual values (obtained from the simulator). However, at some sufficiently low permeability and sufficiently high

Table 6-1 Effects of permeability on the calculated GIIP and their errors

Qg	k	ϕ	h	GIIP (MMscf)			Error of GIIP from a P/Z Plot (%)	
(MMscf/d	(md)	(fraction)	(ft)	Volumetri	Simulatio	PSSE	Using Pavg from Sim.	Using Pavg from PSSE
1	10	0.2	30	6674	6889	6740	+3.2	+1.0
	20	0.2	30	6674	6880	6808	+3.1	+2.0
	50	0.2	30	6674	6880	6852	+3.1	+2.7
	100	0.2	30	6674	6811	6816	+2.1	+2.1
5	10	0.2	30	6674	6833	8271	+2.4	+23.9
	20	0.2	30	6674	6814	7001	+2.1	+4.9
	50	0.2	30	6674	6790	6872	+1.7	+3.0
	100	0.2	30	6674	6779	6722	+1.6	+0.7
10	10	0.2	30	6674	6874	8996	+3.0	+34.8
	20	0.2	30	6674	6839	8295	+2.5	+24.3
	50	0.2	30	6674	6794	6937	+1.8	+3.9
	100	0.2	30	6674	6743	6646	+1.0	-0.4
15	20	0.2	30	6674	6864	9886	+2.9	+48.1
	50	0.2	30	6674	6823	7141	+2.2	+7.0
	100	0.2	30	6674	6796	6834	+1.8	+2.4
	300	0.2	30	6674	6790	6702	+1.7	+0.4
	500	0.2	30	6674	6772	6711	+1.5	+0.6
	1000	0.2	30	6674	6795	6741	+1.8	+1.0

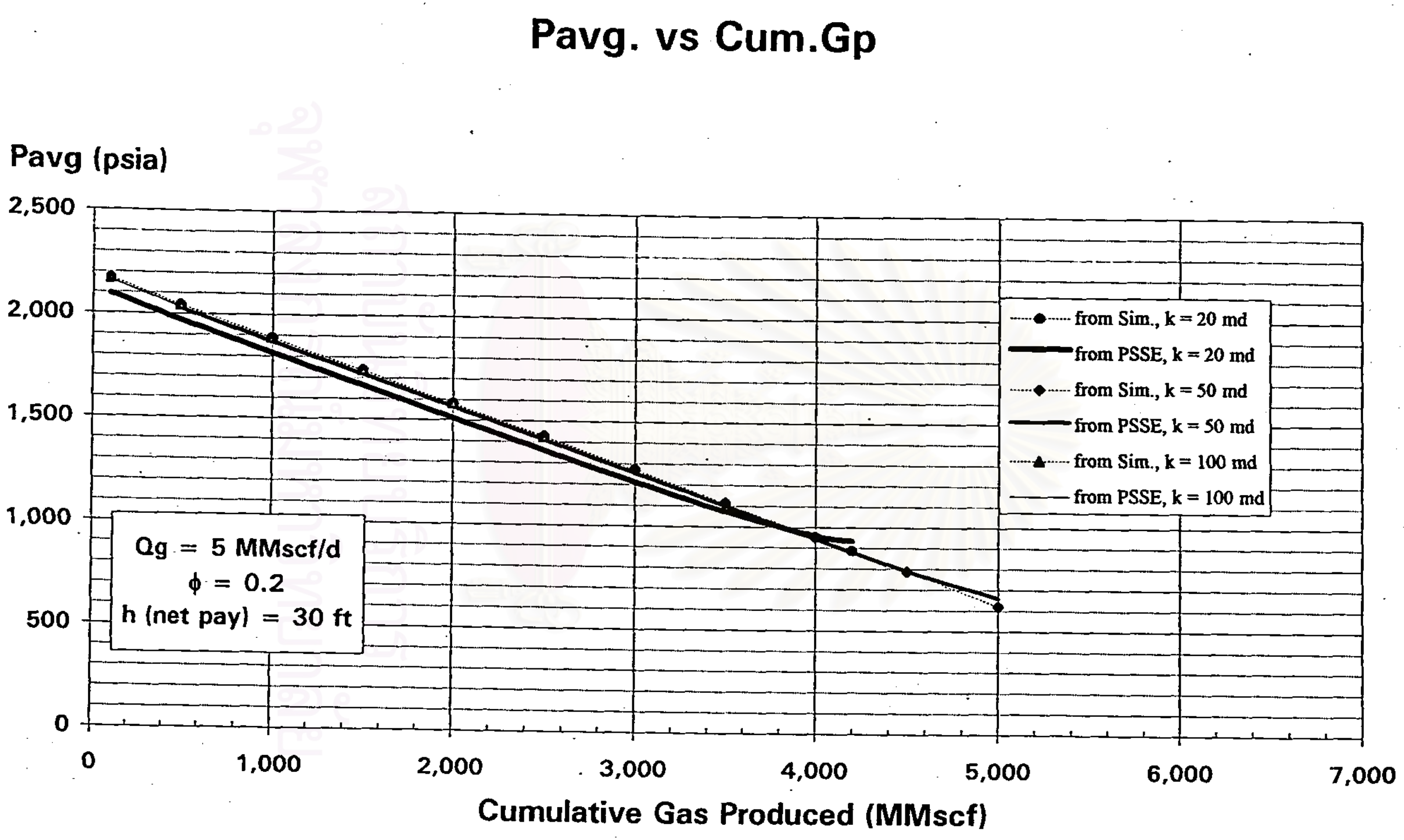

Figure 6-4 Average reservoir pressure as a function of cumulative production (different permeability values, q_g = 5 MMscf/d)

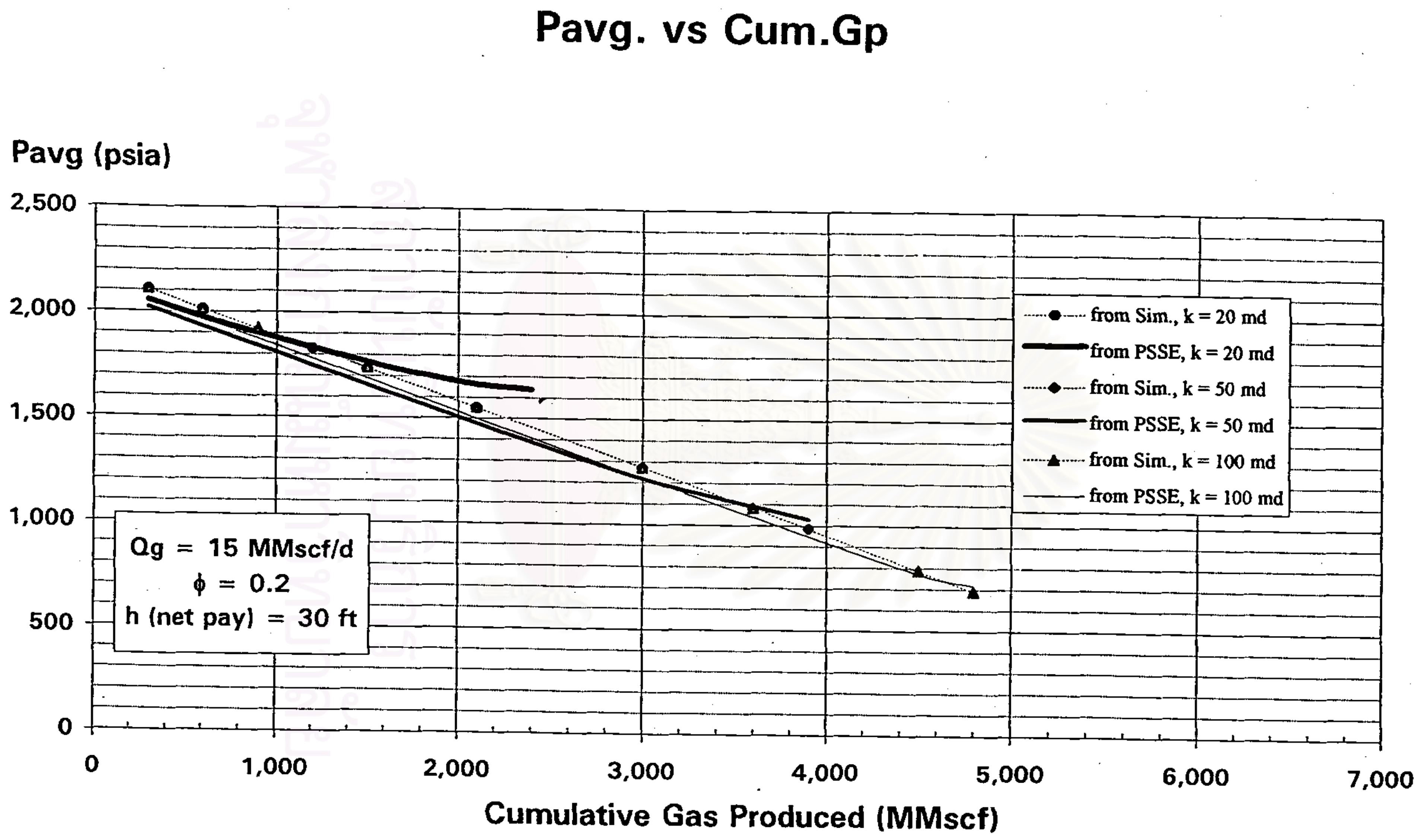

Figure 6-5 Average reservoir pressure as a function of cumulative production (different permeability values, q_g = 15 MMscf/d)

flow rate, $\bar{p}$ values calculated from the pseudo-steady state equation will deviate from the actual values.

In Figure 6-4, with a rate of 5 MMscf/d, the $\bar{p}$'s from the pseudo-steady state equation for k = 100 md practically coincide with all actual values. For k = 50 md, the $\bar{p}$ values obtained from the pseudo-steady state equation deviate from the actual values at high Gp, but for k = 20 md, at early time or small Gp, $\bar{p}$ values obtained from the pseudo-steady state equation are lower than the actual values and at late time (high Gp), the $\bar{p}$ values from the pseudo-steady state equation are higher than the actual values. This kind of behavior (of $\bar{p}$ when k = 20 md) causes the curved shape on the p/z plot, and resulting in difficulty in drawing a straight line and estimation of GIIP. In Figure 6-5, with higher flow rate, the pseudo-steady-state-equation $\bar{p}$ values deviate from the actual values for all values of permeability.

The deviation of the pseudo-steady-state-equation $\bar{p}$ values from the actual values will result in deviation of the practical GIIP from the actual GIIP as shown in Figures 6-6 and 6-7. In these two figures, it can be seen that for each flow rate, there is a threshold value that the errors of the practical GIIP are sufficiently small, such as 5% error. For the 5-MMscf/d flow rate, the threshold value of permeability is about 20 md (Figure 6-6) and for 15-MMscf/d flow rate, the threshold value of permeability is about 60 md (Figure 6-7). The threshold values for various cases are shown in Figure 6-8 which is a plot of permeability and error of the practical GIIP for various flow rates. This plot is prepared from the information in Table 6-1. Figure 6-8 is not intended to be a universal correlation for estimation of threshold values of permeability for various gas rates. In fact, it cannot be a universal correlation because it is prepared

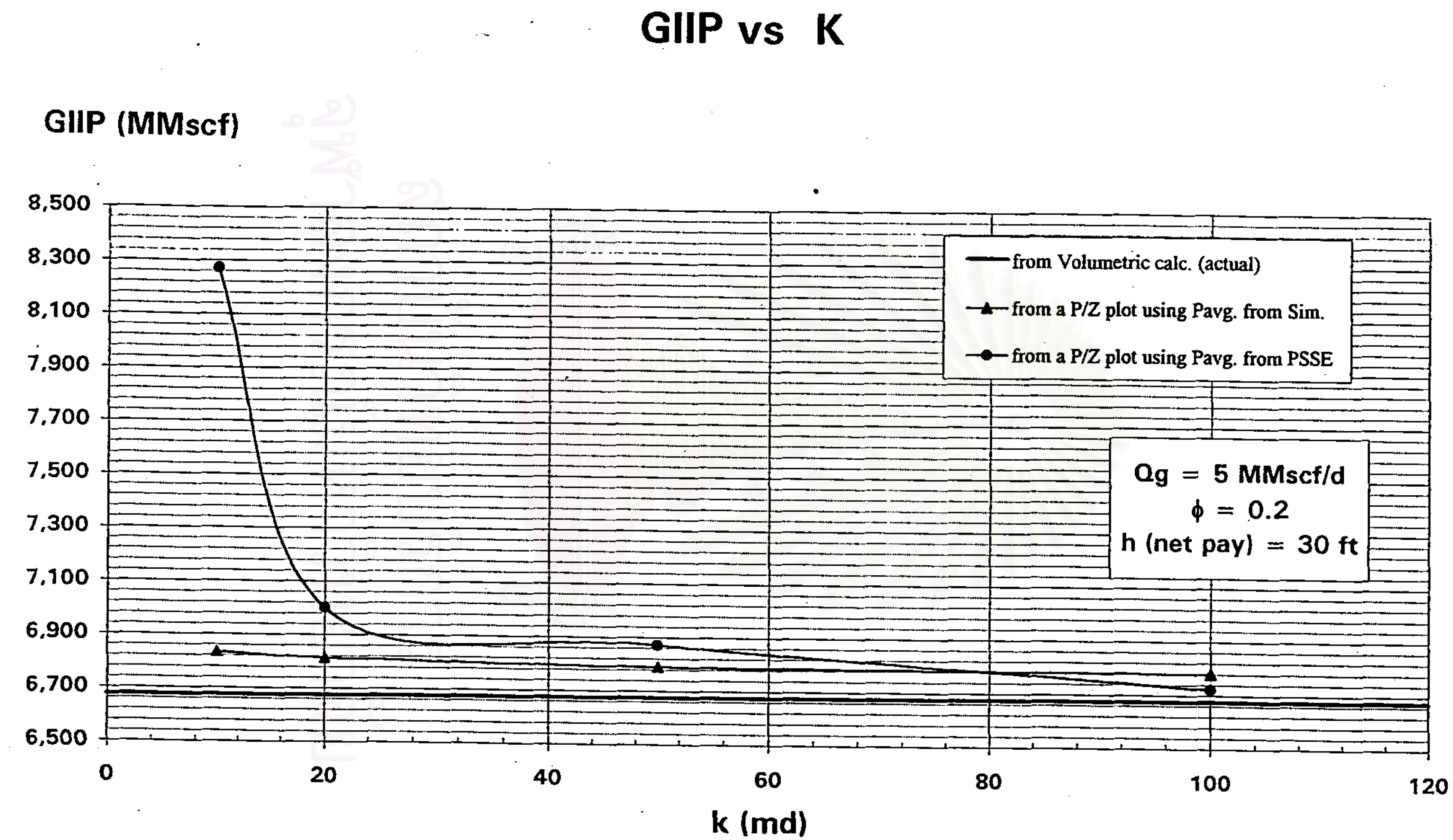

Figure 6-6 GIIP as a function of permeability (q_g = 5 MMscf/d)

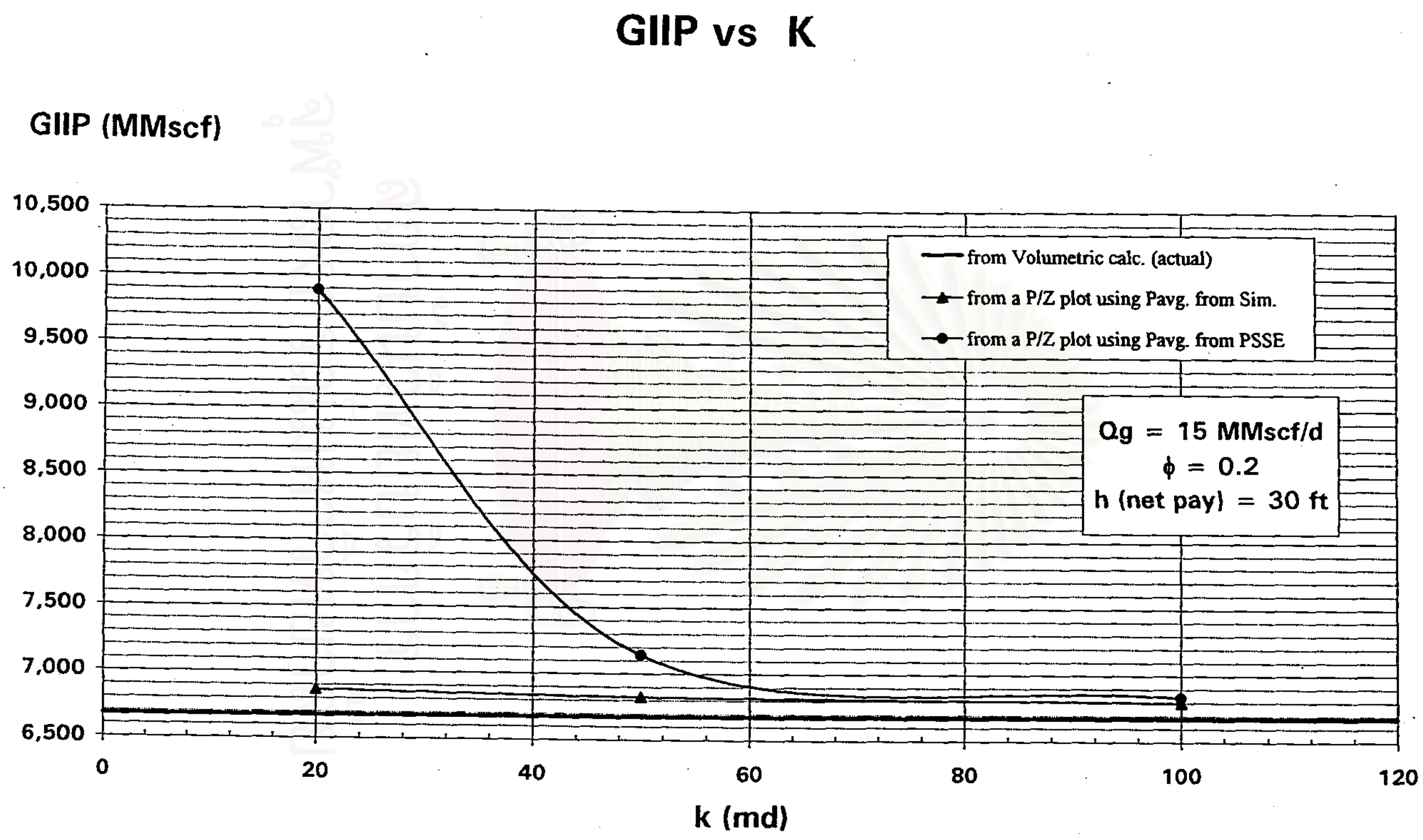

Figure 6-7 GIIP as a function of permeability, q_g = 15 MMscf/d

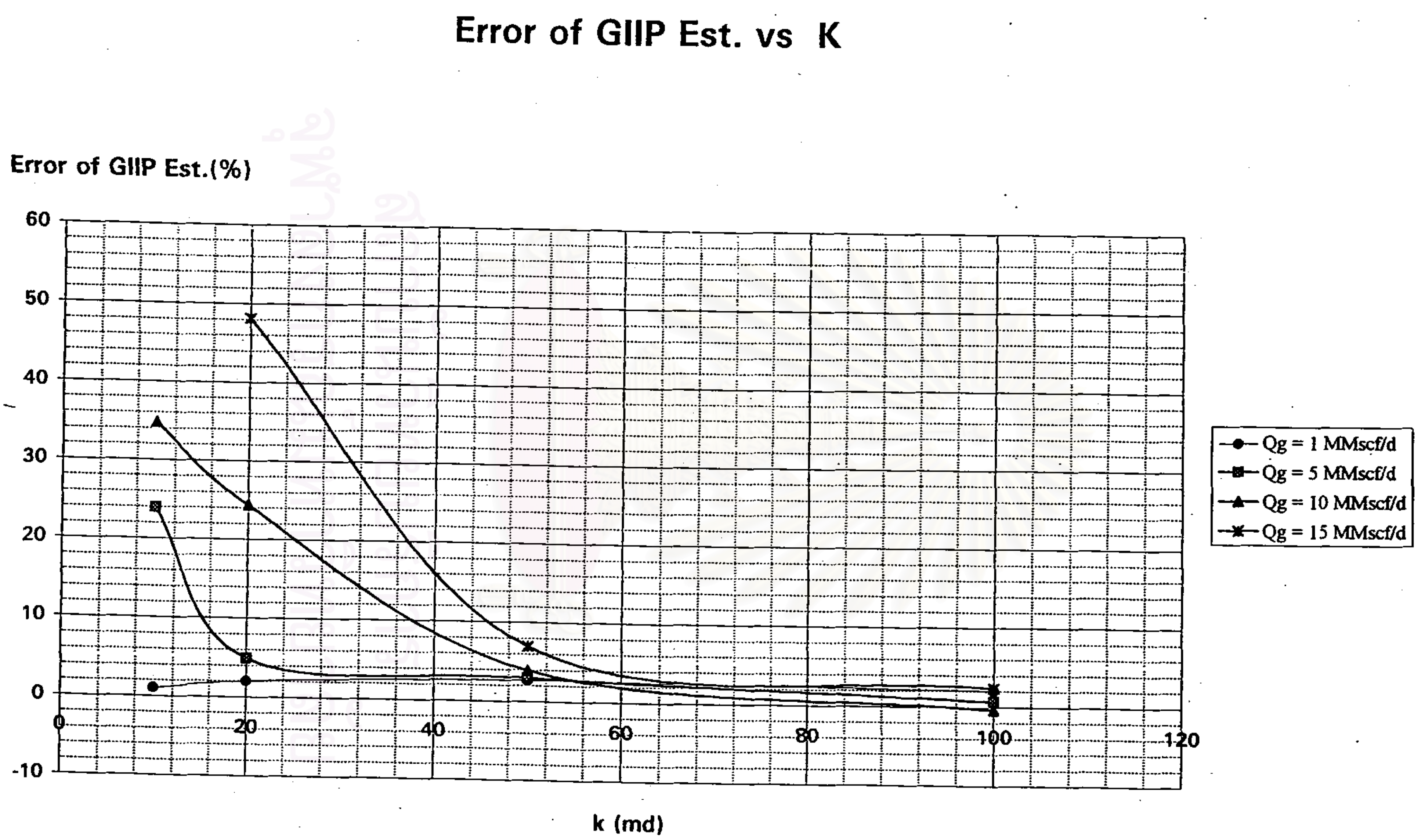

Figure 6-8 Errors of calculated GIIP as a function of permeability at different flow rates

from a specific set of rock and fluid properties and production conditions. This figure is shown for illustrative purpose only. Nevertheless, for a reservoir that has properties and conditions similar to those used in this study, this figure can be used to obtain a threshold value. However, it must be emphasized that the threshold value of permeability presented here is very useful. It equips an engineer with a tool to consider when he can use the material-balance equation or the p/z plot method for a gas reservoir with high confidence. In addition, it is clear that the threshold concept is needed due to deficiency of the pseudo-steady state equation to correctly estimate the average reservoir pressure and does not have anything related to the material-balance equation. Therefore, if one can accurately estimate $\bar{p}$, the p/z plot method can be used to accurately estimate GIIP for all ranges of rock and fluid properties. This is confirmed by a curve with solid triangles in Figures 6-6 and 6-7. This curve shows that reasonably accurate values of GIIP can be obtained for all rock, fluid, and flow properties provided that corrected $\bar{p}$ is available.

6.3 Effect of gas flow rate

Like permeability, flow rate also has effects on the practical GIIP for each specific set of properties and conditions. Table 6-2 shows the actual, material-balance, and practical GIIP values for various sets of properties and conditions. The errors of the material-balance and practical GIIP values are also shown. Similar to the permeability case, the effects of flow rate on the relationship between Gp and $\bar{p}$ are shown in Figures 6-9 and 6-10 for the 20-md and 100-md cases. Variation in flow rate

Table 6-2 Effects of flow rate on the calculated GIIP and their errors

k	Qg	ϕ	h	GIIP (MMscf)			Error of GIIP from a P/Z plot (%)	
(md)	(MMscf/d)	(fraction)	(ft)	Volumetric	Simulation	PSSE	Using Pavg from Sim.	Using Pavg from PSSE
10	1	0.2	30	6,674	6,889	6,740	+3.2	+1.0
	5	0.2	30	6,674	6,833	8,271	+2.4	+23.9
	10	0.2	30	6,674	6,874	8,996	+3.0	+34.8
20	1	0.2	30	6,674	6,880	6,808	+3.1	+2.0
	5	0.2	30	6,674	6,814	7,001	+2.1	+4.9
	10	0.2	30	6,674	6,839	8,295	+2.5	+24.3
	15	0.2	30	6,674	6,864	9,886	+2.9	+48.1
50	1	0.2	30	6,674	6,880	6,852	+3.1	+2.7
	5	0.2	30	6,674	6,790	6,872	+1.7	+3.0
	10	0.2	30	6,674	6,794	6,937	+1.8	+3.9
	15	0.2	30	6,674	6,823	7,141	+2.2	+7.0
100	1	0.2	30	6,674	6,811	6,816	+2.1	+2.1
	5	0.2	30	6,674	6,779	6,722	+1.6	+0.7
	10	0.2	30	6,674	6,743	6,646	+1.0	-0.4
	15	0.2	30	6,674	6,796	6,834	+1.8	+2.4
300	15	0.2	30	6,674	6,790	6,702	+1.7	+0.4
500	15	0.2	30	6,674	6,772	6,711	+1.5	+0.6
1000	15	0.2	30	6,674	6,795	6,741	+1.8	+1.0

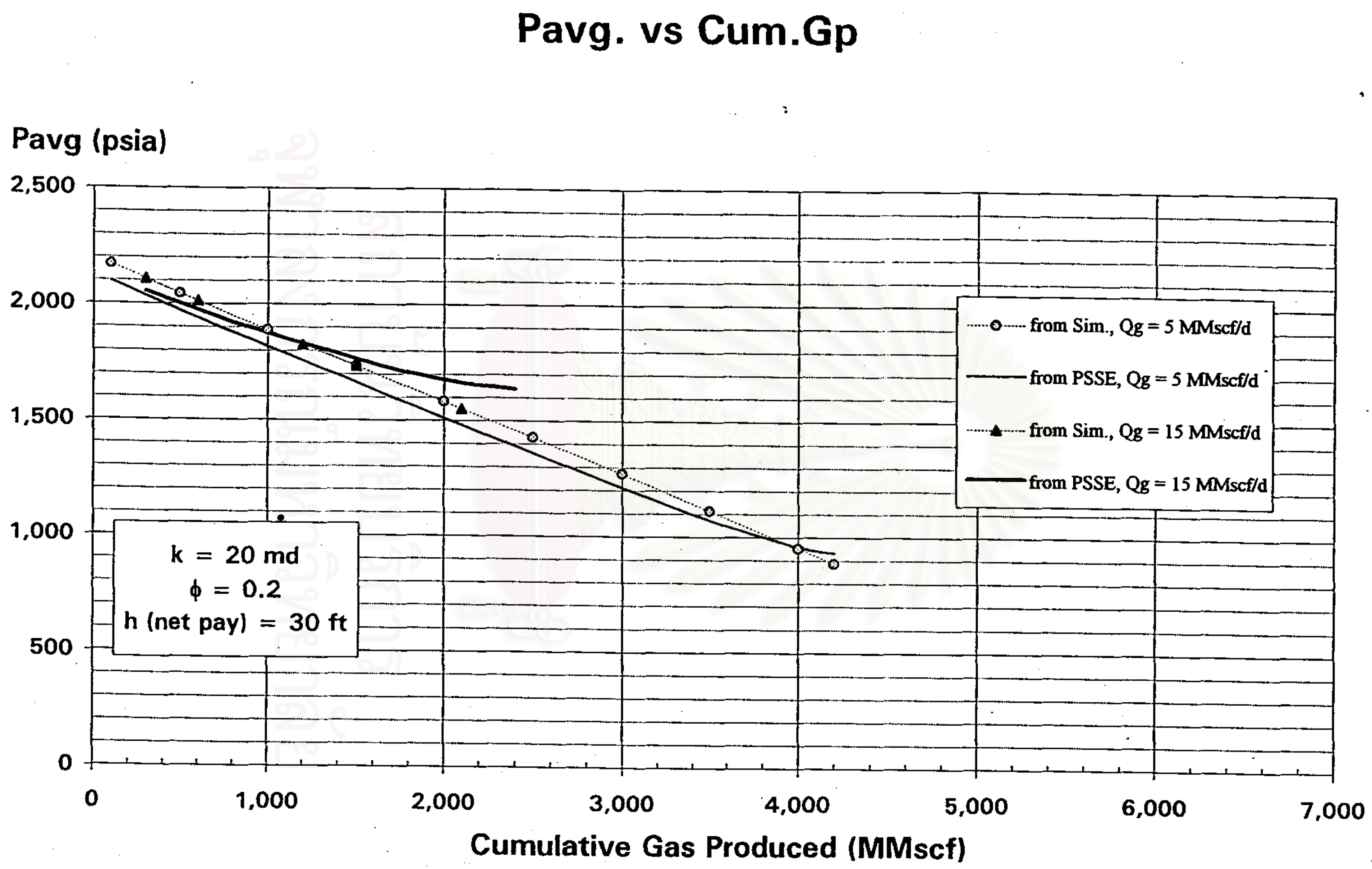

Figure 6-9 Average reservoir pressure as a function cumulative production (different q_g's, k = 20 md)

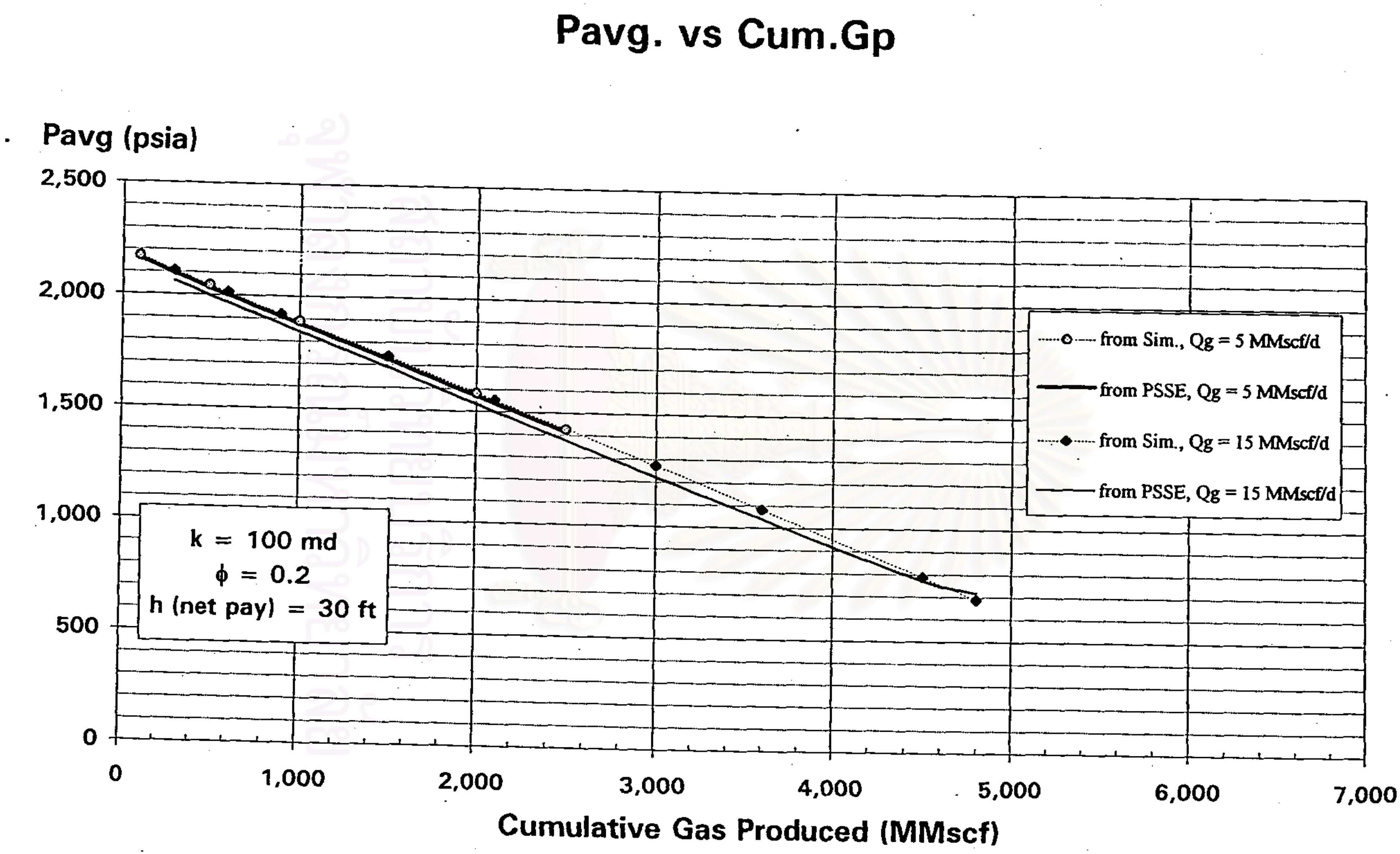

Figure 6-10 Average reservoir pressure as a function of cumulative production (different q_g's, k = 100 md)

does not have any effect on $\bar{p}$, for each Gp, obtained from the simulator (actual $\bar{p}$) for a given gas reservoir system. On the other hand, variation in rates does have effect on $\bar{p}$, for each Gp, obtained from the pseudo-steady state equation. At low permeability, k = 20 md, for the set of properties and conditions used in this study, both 5- MMscf/d and 15-MMscf/d rates cause $\bar{p}$ to deviate from the actual values (Figure 6-9). It is obvious that higher rate causes more deviation. At higher permeability, k = 100 md, rate as high as 15 MMscf/d has little effect on $\bar{p}$ obtained from the pseudo-steady state equation (Figure 6-10). This is likely because at this value of permeability, the rate as high as 15 MMscf/d is still considered to be small to have significant effect on the validity of the pseudo-steady state equation.

Figures 6-11 and 6-12 show the influence of flow rate on the material-balance and the practical GIIP values for k = 20 md and k = 100 md, respectively. Again, one can see that for the case of the material balance GIIP, flow rate does not have an effect because $\bar{p}$ values are the actual ones and are not under the influence of flow characteristics. On the other hand, because $\bar{p}$ values calculated from the pseudo-steady-state equation are under the influence of flow characteristics, flow rate have impact on the practical GIIP. However, the impact can be seen only in Figure 6-11, but not in Figure 6-12. This is because the rate as high as 15 MMscf/d is still considered too low to have any significant effect on the practical GIIP, as discussed before. From Figure 6-11, it can be seen that there exists a threshold value of gas flow rate below which the rate does not have any influence on the practical GIIP values. The threshold value concept is confirmed by various curves in Figure 6-13. In this figure, if 5% error of the GIIP is acceptable, the threshold values of rates for

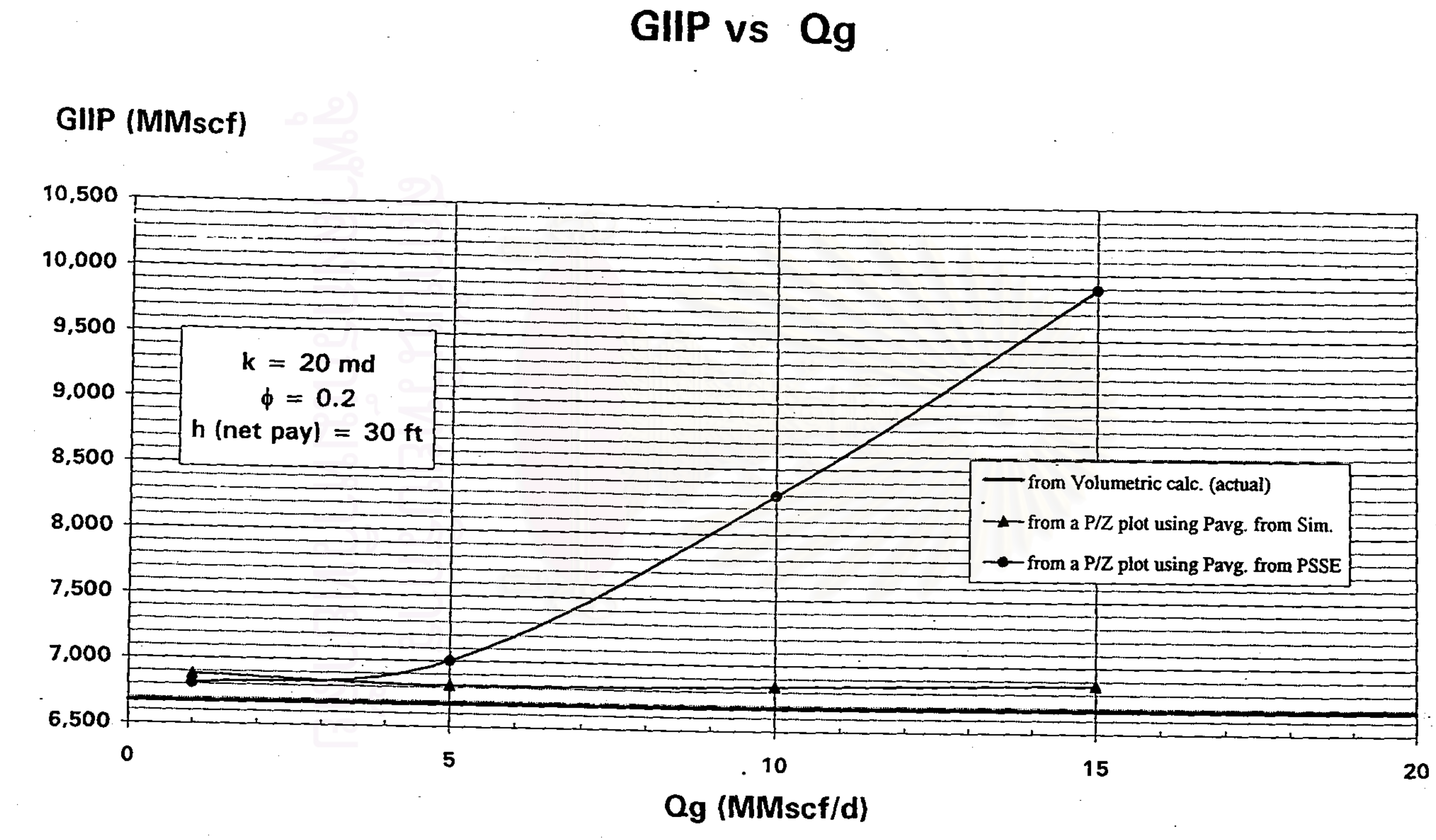

Figure 6-11 GIIP as a function of flow rate (k = 20 md)

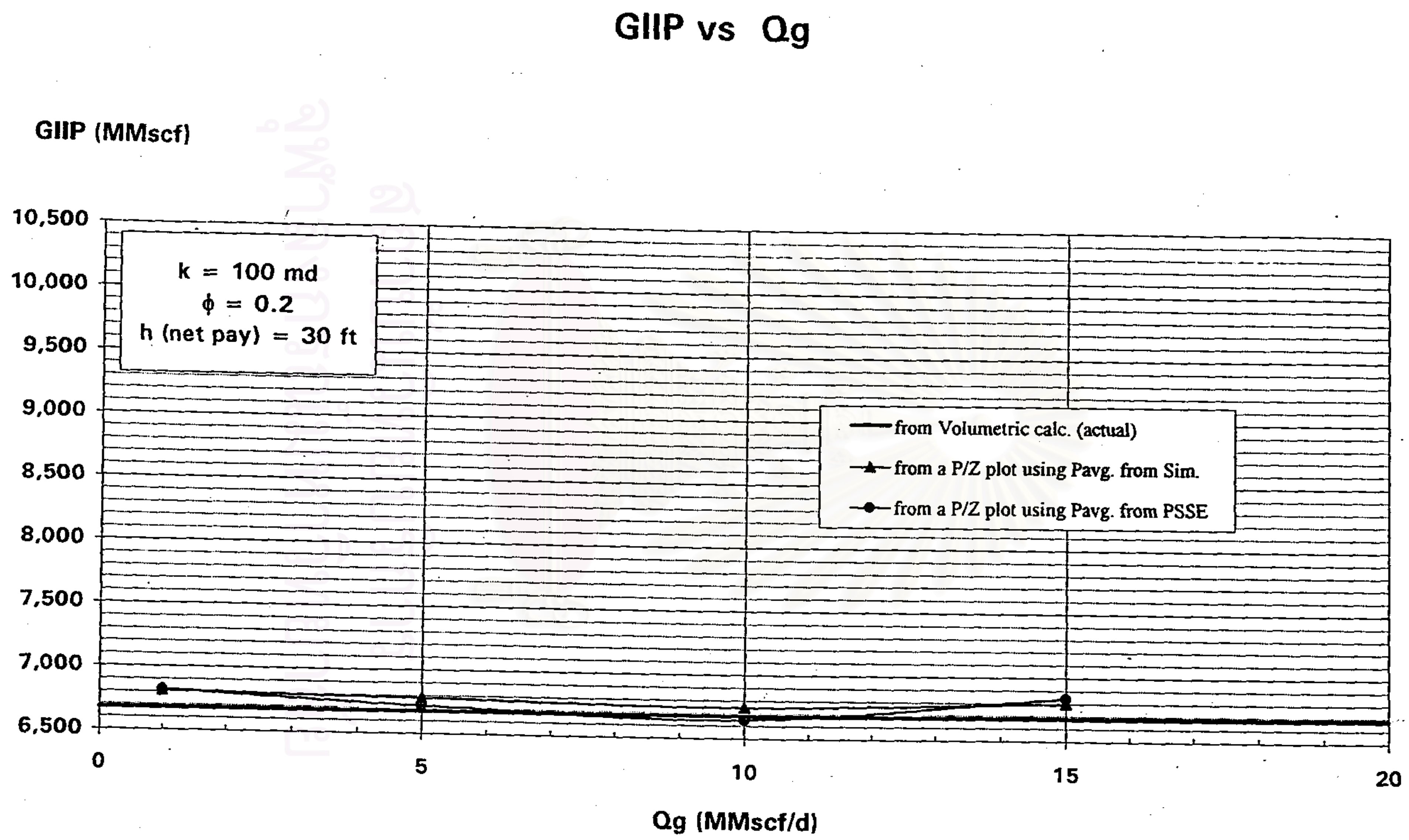

Figure 6-12 GIIP as a function of flow rate (k = 100 md)

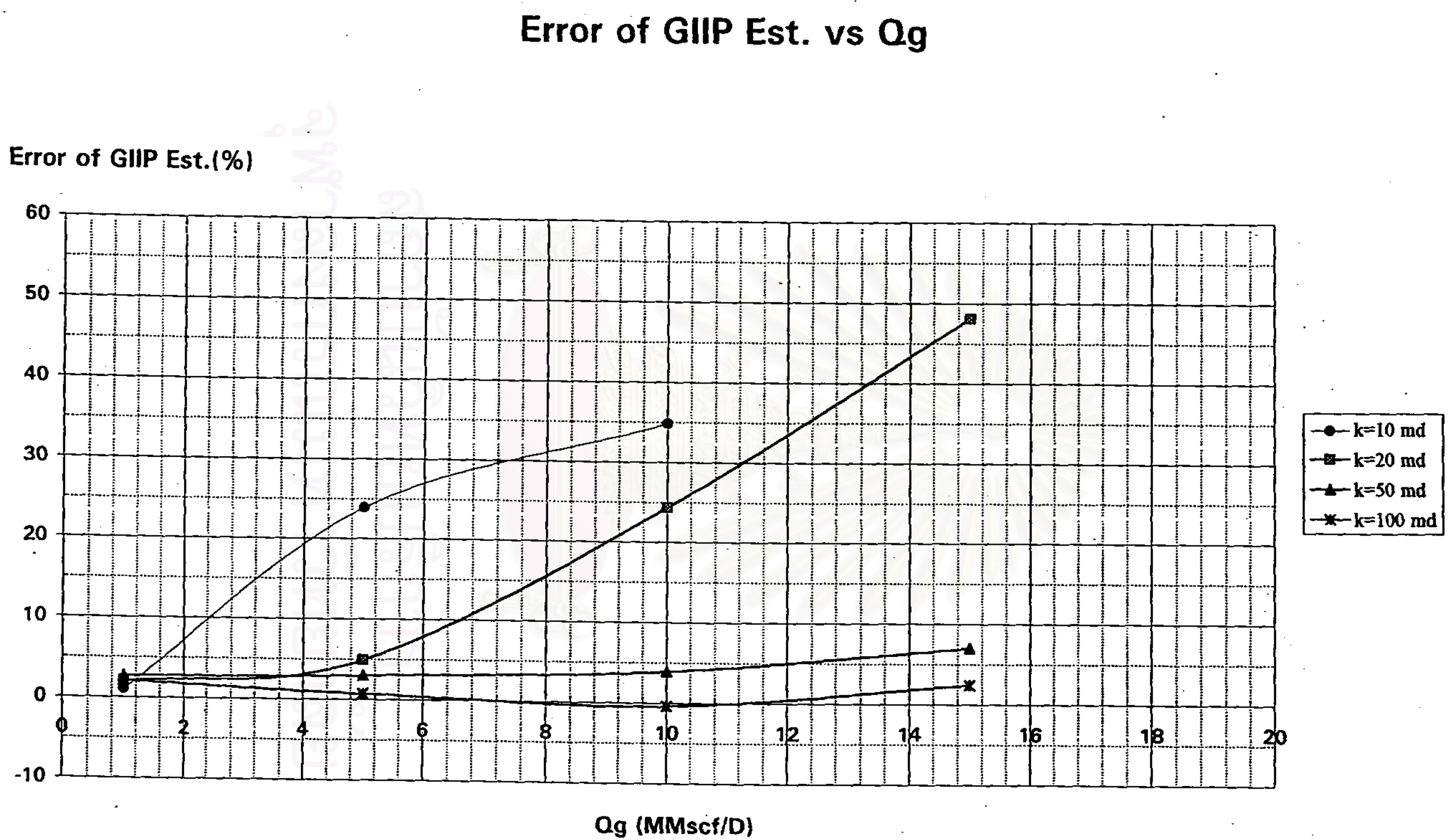

Figure 6-13 Errors of calculated GIIP as a function of flow rate at different values of permeability

10-md, 20-md, 50-md and 100-md cases are 1.6, 5, 12, and greater than 15 MMscf/d, respectively. Again, Figure 6-13 is not intended to be generalized for all gas reservoir systems. However, it can be used for the reservoir system that has properties and conditions similar to the ones used in this study.

6.4 Effects of porosity and thickness

Parameters used in evaluation of GIIP are fixed except porosity to see its effects on the calculated GIIP. This is also done for the thickness. Table 6-3 shows the effects of porosity and thickness on calculated GIIP. Flow rate of 15 MMscf/d and permeability value of 100 md were used for all cases. Porosity values used in the study were 10%, 20% and 30% with a constant thickness of 30 feet. For the study of the effect of thickness, six values of thickness were used which were 15, 20, 30, 60, 90 and 120 feet. The values of the actual, material-balance, and practical GIIP were calculated in the same way as what were done in the previous studies (effects of permeability and flow rate).

The material-balance GIIP for all values of porosity used in the study are very close to the actual GIIP (less than 2% errors). This is practically not of significant magnitude considered that the discrepancies are partially the result of inconsistent use of z-factor values. The practical GIIP values also show small deviation from the actual GIIP values (less than 3%). From the study, it can be said that changing porosity values will vary only the magnitude of GIIP's (the actual, material-balance, and the practical GIIP's), but not the deviations (errors) of the calculated GIIP's from a p/z

Table 6-3 Effects of porosity and thickness on the calculated GIIP and their errors

Qg (MMscf/d)	k (md)	ϕ (fraction)	h (ft)	GIIP (MMscf)			Error of GIIP from a P/Z plot (%)	
				Volumetric	Simulation	PSSE	Using Pavg from Sim.	Using Pavg from PSSE
15	100	0.1	30	3,337	3,374	3,408	+1.1	+2.1
		0.2	30	6,674	6,796	6,834	+1.8	+2.4
		0.3	30	10,011	10,096	10,184	+0.8	+1.7
		0.2	15	3,337	3,377	3,449	+1.2	+3.4
		0.2	20	4,449	4,485	4,684	+0.8	+5.3
		0.2	60	13,348	13,433	13,378	+0.6	+0.2
		0.2	90	20,023	20,241	20,052	+1.1	+0.1
		0.2	120	26,697	27,136	26,954	+1.6	+1.0

plot (the material-balance, and the practical GIIP's) from the actual GIIP. This can be explained by Figure 6-14. For all values of porosity used in the study, $\bar{p}$ values obtained from the pseudo-steady state equation are close to the actual $\bar{p}$ values obtained from the simulator. A similar behavior can also be observed in the study of the effect of thickness. For all values of thickness used in the study, $\bar{p}$ values from the pseudo-steady state equation are close to the actual $\bar{p}$ values (Figure 6-15). The material-balance and practical GIIP's of reservoirs with various thicknesses and their errors are also presented in Table 6-3. Considering the errors, one sees that they are quite low. It, therefore, can be concluded that the effect of thickness on the material-balance and practical GIIP's are very small and insignificant.

6.5 Effect of gas gravity

As it is known that gas gravity affects gas deviation factor (z factor), or gas formation volume factor (B_g), the gas gravity is then expected to affect magnitude of GIIP. The study of the effects of gas gravity on the material-balance and practical GIIP's was, therefore, carried out. The values of gas flow rate used in the study were 1, 5, 10, and 15 MMscf/d, while the permeability values were 20, 50, and 100 md. The studied values of the gas specific gravity were 0.7, 0.8, and 0.9. The results of the study are illustrated in Table 6-4.

From Table 6-4, at the gas flow rate of 1 MMscf/d and permeability of 20, 50, and 100 md, the errors of the material-balance GIIP (deviation from the actual GIIP) for various gas specific gravity values are all within 5%. Although the errors of the material-balance GIIP are slightly increasing with increasing gas specific gravity, for

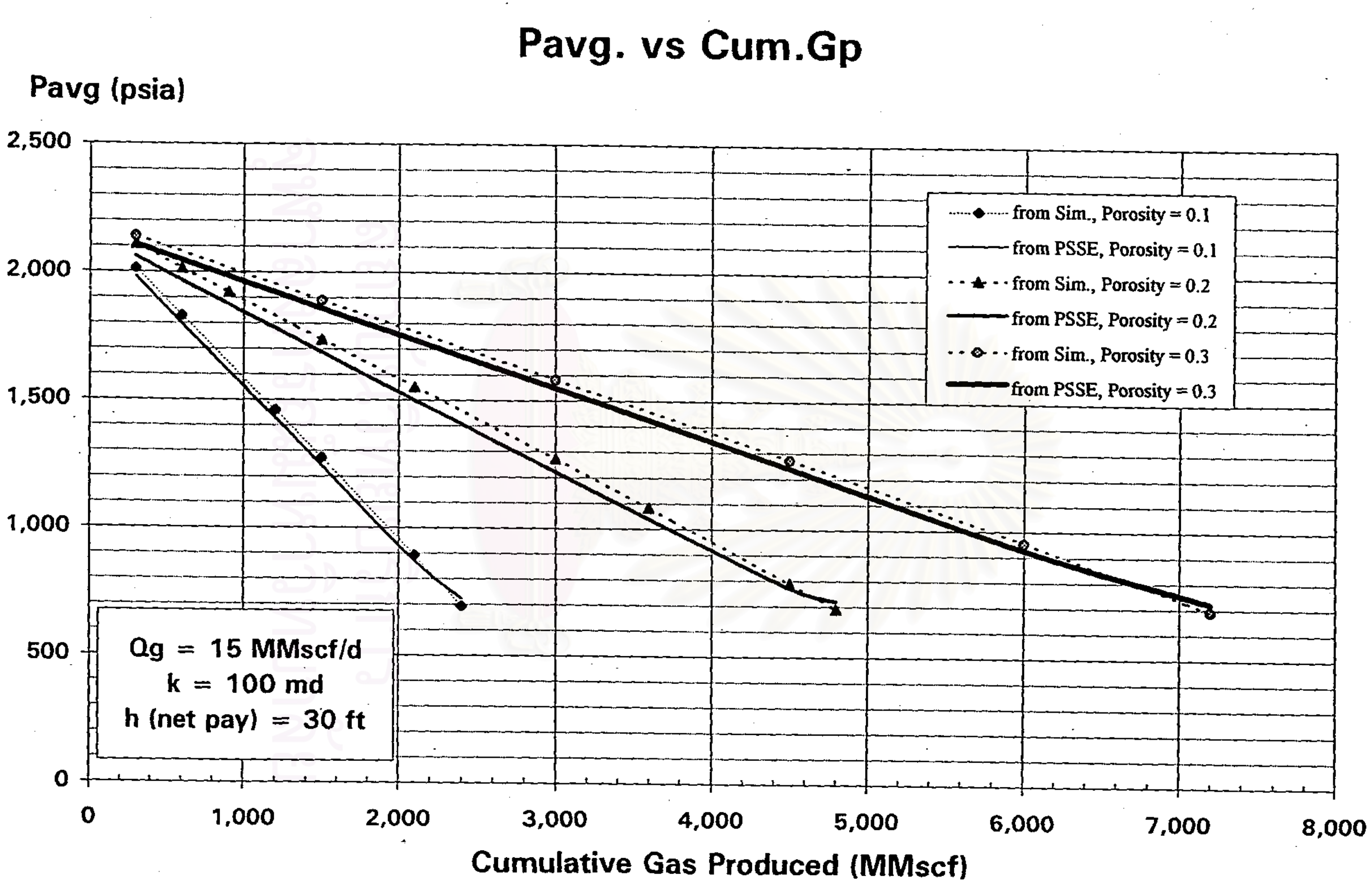

Figure 6-14 Average reservoir pressure as a function of cumulative production (different porosity values, q_g = 15 MMscf/d, k = 100 md)

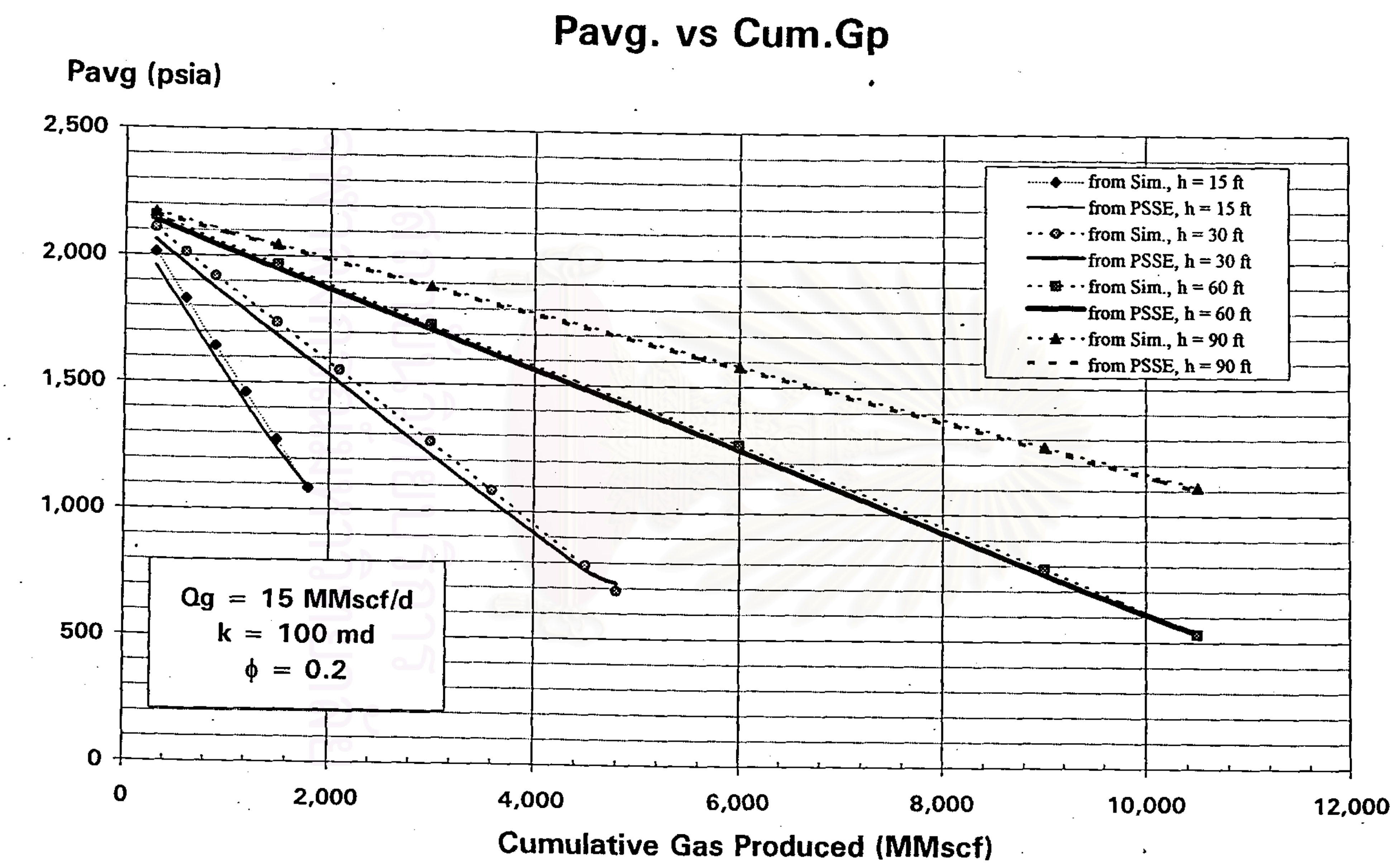

Figure 6-15 Average reservoir pressure as a function of cumulative production (different thickness values, q_g = 15 MMscf/d, k = 100 md)

Table 6-4 Effects of gas gravity on the calculated GIIP and their errors

Qg (MMscf/d)	SG gas (air = 1.0)	k (md)	GIIP (MMscf)			Error of GIIP from a P/Z plot (%)	
			Volumetric	Simulation	PSSE	Using Pavg from Sim.	Using Pavg from PSSE
1	0.7	20	6,356	6,511	6,464	+2.4	+1.7
		50	6,356	6,511	6,493	+2.4	+2.2
		100	6,356	6,511	6,504	+2.4	+2.3
	0.8	20	6,674	6,880	6,808	+3.1	+2.0
		50	6,674	6,880	6,852	+3.1	+2.7
		100	6,674	6,811	6,816	+2.1	+2.1
	0.9	20	7,088	7,381	7,330	+4.1	+3.4
		50	7,088	7,381	7,352	+4.1	+3.7
		100	7,088	7,381	7,361	+4.1	+3.9
5	0.7	20	6,356	6,453	6,883	+1.5	+8.3
		50	6,356	6,436	6,517	+1.3	+2.5
		100	6,356	6,438	6,456	+1.3	+1.6
	0.8	20	6,674	6,814	7,001	+2.1	+4.9
		50	6,674	6,790	6,872	+1.7	+3.0
		100	6,674	6,779	6,722	+1.6	+0.7
	0.9	20	7,088	7,288	7,781	+2.8	+9.8
		50	7,088	7,259	7,291	+2.4	+2.9
		100	7,088	7,255	7,213	+2.4	+1.8
10	0.7	20	6,356	6,478	7,665	+1.9	+20.6
		50	6,356	6,451	6,677	+1.5	+5.0
		100	6,356	6,433	6,469	+1.2	+1.8
	0.8	20	6,674	6,839	8,295	+2.5	+24.3
		50	6,674	6,794	6,937	+1.8	+3.9
		100	6,674	6,743	6,646	+1.0	-0.4
	0.9	20	7,088	7,331	8,591	+3.4	+21.2
		50	7,088	7,276	7,533	+2.6	+6.3
		100	7,088	7,249	7,336	+2.3	+3.5
15	0.7	20	6,356	6,484	9,315	+2.0	+46.6
		50	6,356	6,461	6,845	+1.7	+7.7
		100	6,356	6,449	6,619	+1.5	+4.1
	0.8	20	6,674	6,864	9,886	+2.9	+48.1
		50	6,674	6,823	7,141	+2.2	+7.0
		100	6,674	6,796	6,834	+1.8	+2.4
	0.9	20	7,088	7,350	10,817	+3.7	+52.6
		50	7,088	7,281	7,914	+2.7	+11.7
		100	7,088	7,264	7,350	+2.5	+3.7

example, at q_g = 1 MMscf/d, k = 20 md, the errors are 2.4%, 3.1% and 4.1% for gas specific gravity of 0.7, 0.8 and 0.9, respectively, they are considered to be not of significant difference (all less than 5%). At higher flow rates (5, 10, and 15 MMscf/d), the same observations were made. Therefore, it can be said that for any flow rate and permeability values, gas gravity has no effect on the material-balance GIIP.

The deviations of the practical GIIP from the actual GIIP at different gas gravity values given constant gas flow rate and permeability values are considered to be in the same range (for example, at the flow rate of 5 MMscf/d, permeability of 50 md, the errors of the practical GIIP for gas gravity of 0.7, 0.8 and 0.9 are 2.5%, 3.0% and 2.9%, respectively). It can also be seen in Figure 6-16 that the differences between the practical and the actual GIIP's are about the same for all the studied values of gas gravity at the same permeability value. A similar plot was generated again, but varying flow rate in stead of permeability (Figure 6-17). The errors of the practical GIIP calculated at the same flow rate for different gas specific gravity values vary randomly within a small range which is considered to be insignificant. Therefore, gas gravity can be considered to have insignificant effect on the deviations of the material-balance and practical GIIP's from the actual value.

Another interesting point to mentioned here is that for any value of gas specific gravity, the error of the practical GIIP is higher when gas flow rate increases and/or permeability decreases (for example, at gas specific gravity of 0.8; q_g = 5 MMscf/d, k = 20 md, the error of the practical GIIP is 4.9%; at q_g = 15 MMscf/d, k = 20md, the error is 48.1%; and at q_g = 15 MMscf/d, k = 100 md, the error is 2.4%). (This also confirms the previous studies of the effects of permeability and flow rate on the

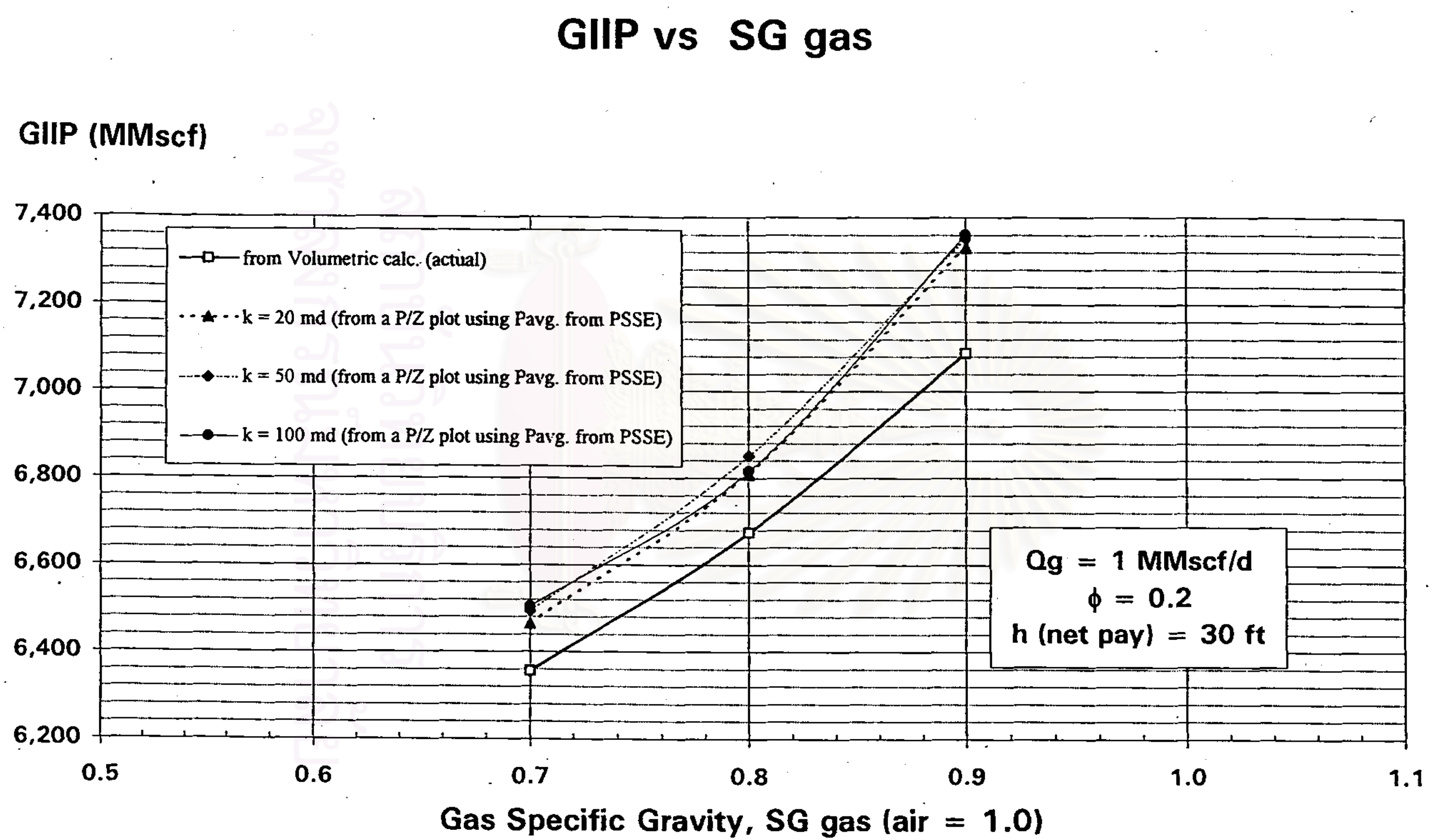

Figure 6-16 GIIP as a function of gas gravity (q_g = 1 MMscf/d)

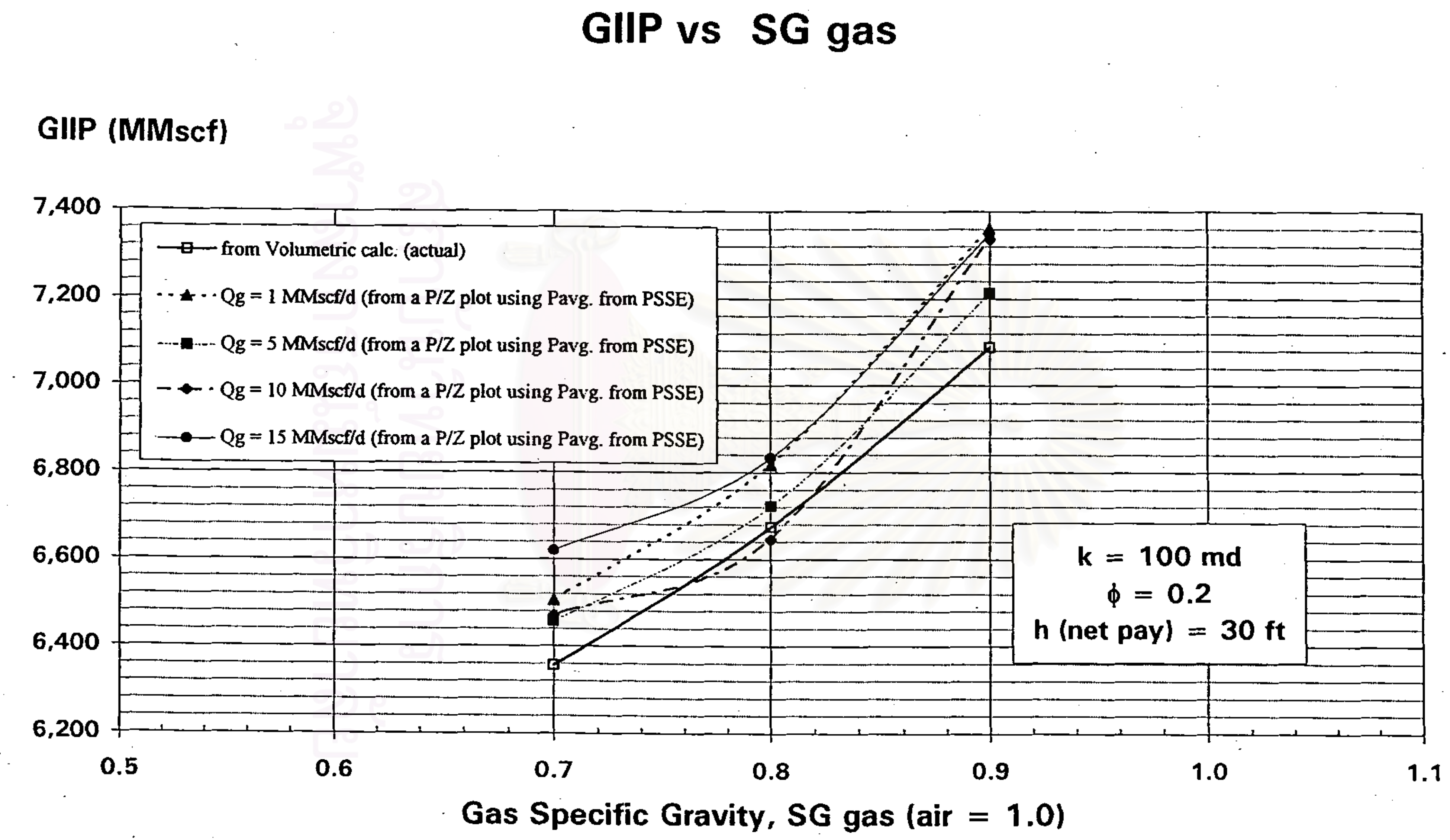

Figure 6-17 GIIP as a function of gas gravity (k=100 md)

practical GIIP.) It can be explained by Figures 6-18 and 6-19. Plots of $\bar{p}$ vs. Gp for various gas specific gravity values at 5 MMscf/d, 100 md (as in Figure 6-18) and at 10 MMscf/d, 20 md (as in Figure 6-19) were prepared. In the case with lower gas flow rate and higher permeability (Figure 6-18), values of $\bar{p}$ from the pseudo-steady state equation are closer to the actual values.

6.6 Effect of impurities

Impurities in gas are mainly CO_2, and N_2. Other substances may be found in a minor quantity. Therefore, the study will focused only on CO_2 and N_2. As it is known that CO_2 and N_2 affect z factor, it is the purpose of the study to investigate whether they have any effect on the calculated GIIP's (material-balance and practical GIIP's). The CO_2 concentrations used in this study are 0% and 10% mole, while N_2 concentrations are 0% and 0.5% mole. The flow rate and permeability used are 15 MMscf/d and 100 md, respectively. Combined gas specific gravity was fixed at 0.8. The values of z factor for each combination of natural gas, CO_2 and NO_2 were calculated by Dranchuk-Abou-Kassem equation and shown in Table 6-5.

Table 6-5 Z factors of natural gas of four different impurity concentrations.

P	z factor			
(psia)	CO2=0, N2=0	CO2=0, N2=0.5%	CO2=10%, N2=0	CO2=10%, N2=0.5%
750	0.940	0.940	0.950	0.950
900	0.930	0.931	0.942	0.942
1200	0.912	0.913	0.927	0.928
1500	0.899	0.900	0.916	0.917
1800	0.890	0.891	0.908	0.909

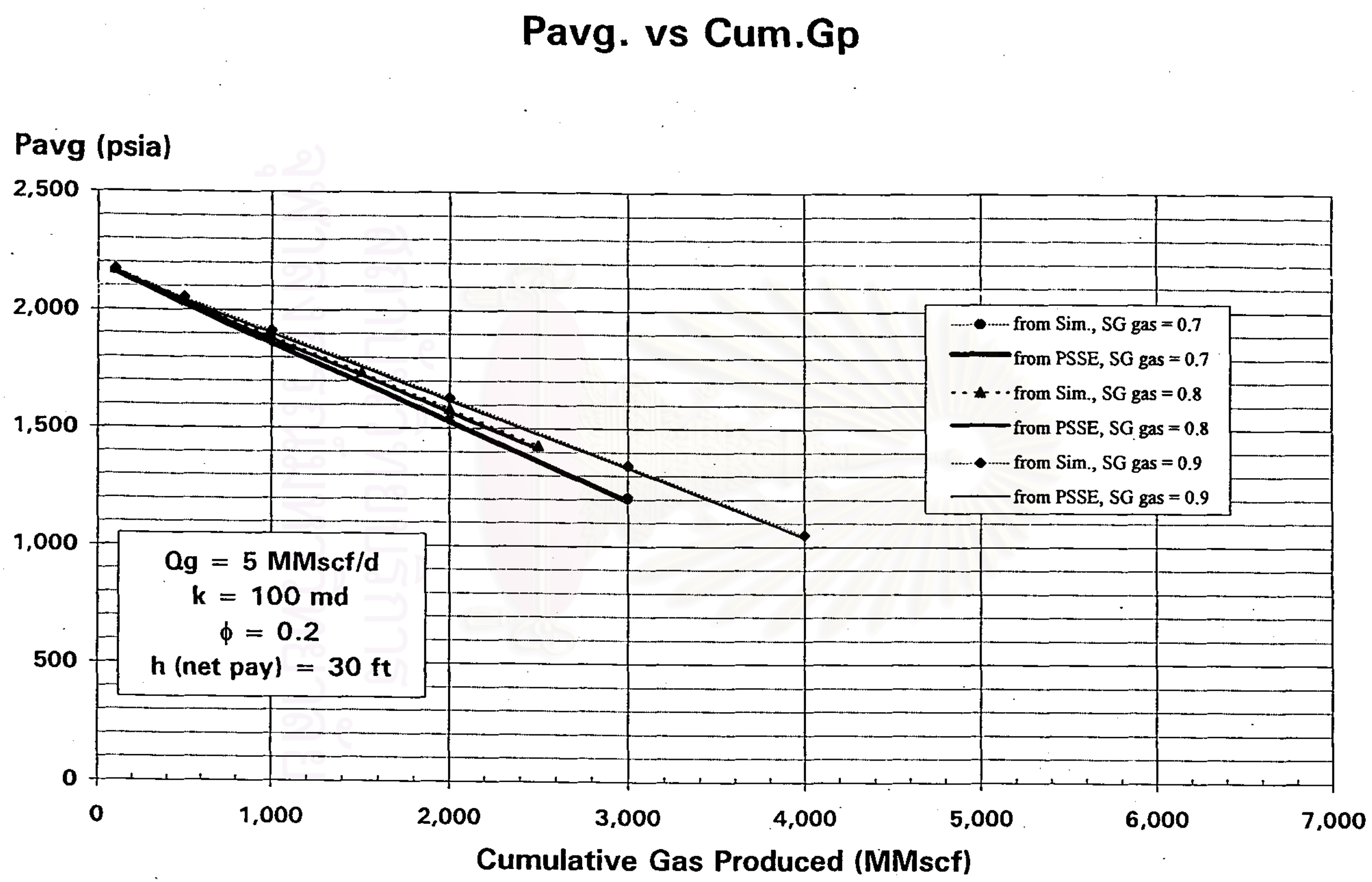

Figure 6-18 Average reservoir pressure as a function of cumulative production (different gas gravity values, q_g = 5 MMscf/d)

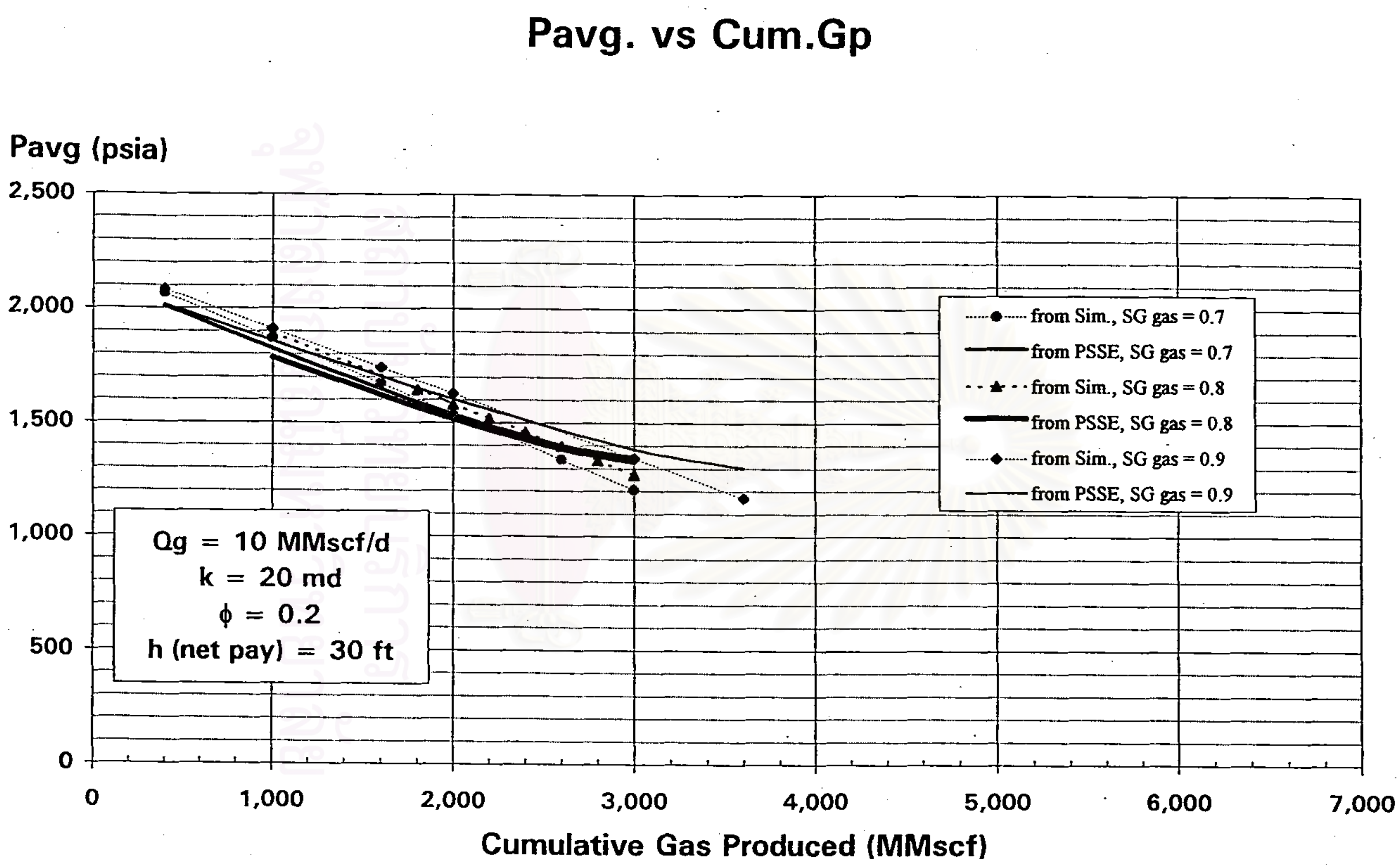

Figure 6-19 Average reservoir pressure as a function of cumulative production (different gas gravity values, q_g = 10 MMscf/d)

The results of the study are illustrated in Table 6-6.

Table 6-6 Calculated GIIP of natural gas of four different impuritiy concentrations.

SG of the Natural	GIIP (MMscf)			Error of GIIP from a P/Z plot (%)	
Gas = 0.8	Volumetric	Simulation	PSSE	Using Pavg from Sim.	Using Pavg from PSSE
CO_2 = 0 , N_2 = 0	6,674	6,796	6,834	+1.8	+2.4
CO_2 = 10% , N_2 = 0	6,674	6,796	6,967	+1.8	+4.4
CO_2 = 0 , N_2 = 0.5%	6,674	6,807	6,927	+2.0	+3.8
CO_2 = 10% , N_2 = 0.5%	6,674	6,796	6,972	+1.8	+4.5

From Table 6-5, as expected, for higher CO_2 and/or N_2 concentrations, z factor will increase (natural gas containing impurities has higher z factor than pure natural gas). From Table 6-6, for any impurities concentraion, the errors of the material-balance GIIP are small and about the same (1.8% - 2.0%), so do those of the practical GIIP (2.4% - 4.5%). Small deviation of the practical GIIP values from the actual values depends on the accuracy of the calculated $\bar{p}$ from the pseudo-steady state equation. The practical GIIP derived from $\bar{p}$'s obtained from the pseudo-steady state equation, so if the pseudo-steady-state-equation $\bar{p}$'s are approaching closely to the actual values, the resulting GIIP is also going to be close to the actual GIIP. This is the case as seen in Figure 6-20 , where $\bar{p}$ values from the two sources almost coincide for all concentrations of impurities.

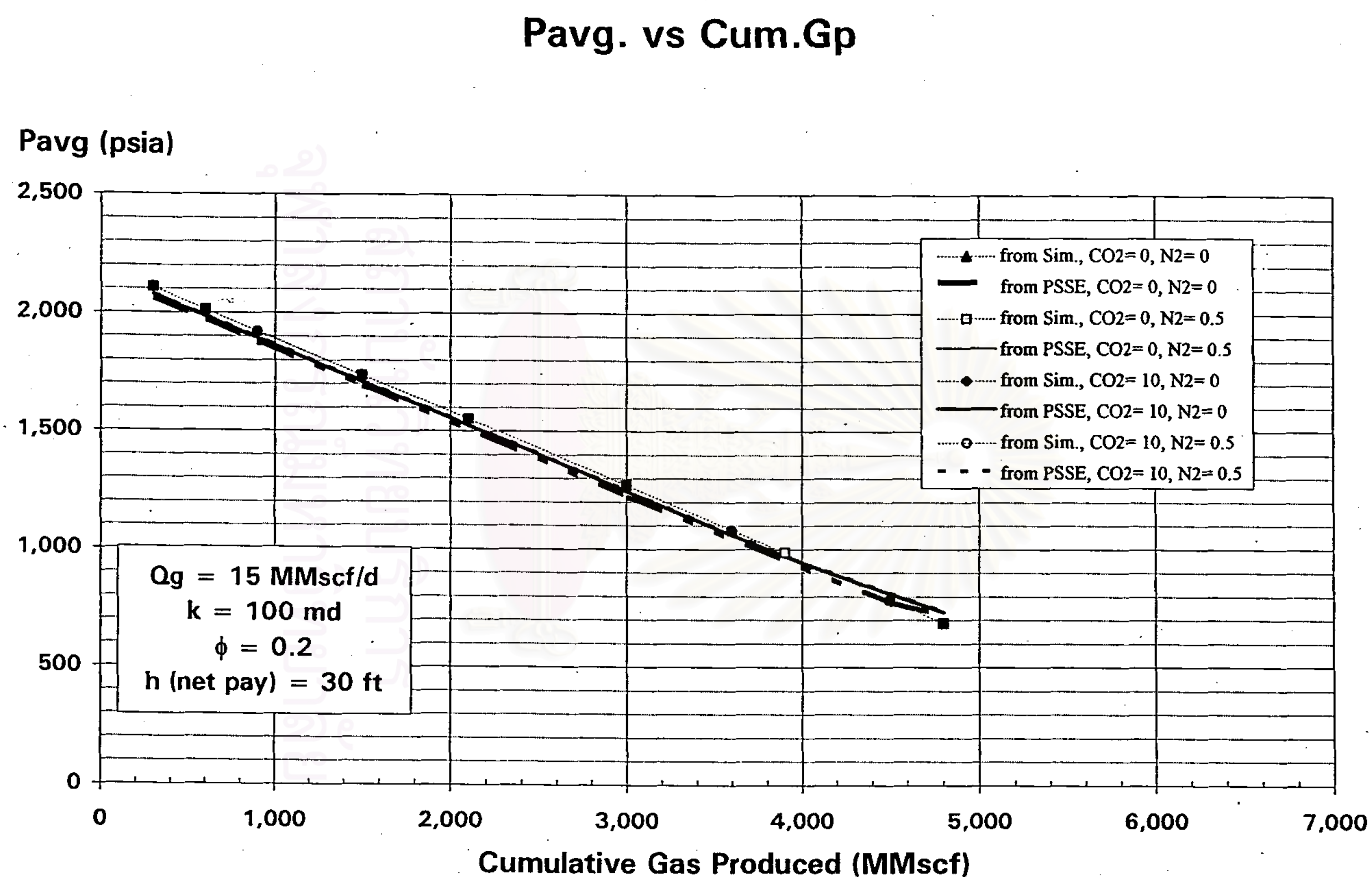

Figure 6-20 Average reservoir pressure as a function of cumulative production (different impurity concentrations, q_g = 15 MMscf/d)

6.7 Effect of skin factor

Skin factor indicates how damaged the area around the wellbore is. The positive skin indicates difficulty of reservoir fluid flowing into the well. The positive skin yields extra pressure drop around the wellbore (in the damaged zone).

The value of permeability used in this study is 100 md (which is high enough to see the effects of the skin, if any, clearly). While, the gas flow rates are 5, and 15 MMscf/d. The studied values of the skin are 0, 5, and 20. The results of the study are shown in Table 6-7. At low flow rate of 5 MMscf/d, there is practically no effect of skin on the errors of both the material-balance and practical GIIP's. The deviations range from as small as 0.1% to 2% which is considered to be in significance. However, an interesting point to see is when flow rate rises up to 15 MMscf/d, errors of GIIP's resulting from $\bar{p}$'s obtained from the pseudo-steady state equation are progressively increasing from 2.4% in the case of no skin to 33.3% in the case of the skin factor of 20, while the material-balance GIIP's are not affected. This leads to an investigation of the effect of skin on $\bar{p}$ which is the only parameter derived from different sources. It is obvious from the Figures 6-21 and 6-22 that at higher flow rate, 15 MMscf/d, $\bar{p}$'s from the pseudo-steady state equation for the skinned cases deviate from the actual $\bar{p}$'s. As shown earlier, at the same flow rate and permeability values with no skin, the deviation is not as high (from Tables 6-1 and 6-2). Therefore, skin is another factor affecting flow performance of gas in the reservoir. Like low permeability, high skin impedes flow of gas in the reservoir, hence making it behave

Table 6-7 Effects of skin factor on the calculated GIIP and their errors

Qg (MMscf/d)	Skin Factor	GIIP (MMscf)			Error of GIIP from a P/Z plot (%)	
		Volumetric	Simulation	PSSE	Using Pavg from Sim.	Using Pavg from PSSE
5	0	6,674	6,807	6,721	+2.0	+0.7
	5	6,674	6,800	6,682	+1.9	+0.1
	20	6,674	6,800	6,779	+1.9	+1.6
15	0	6,674	6,794	6,834	+1.8	+2.4
	5	6,674	6,814	7,108	+2.1	+6.5
	20	6,674	6,807	8,896	+2.0	+33.3

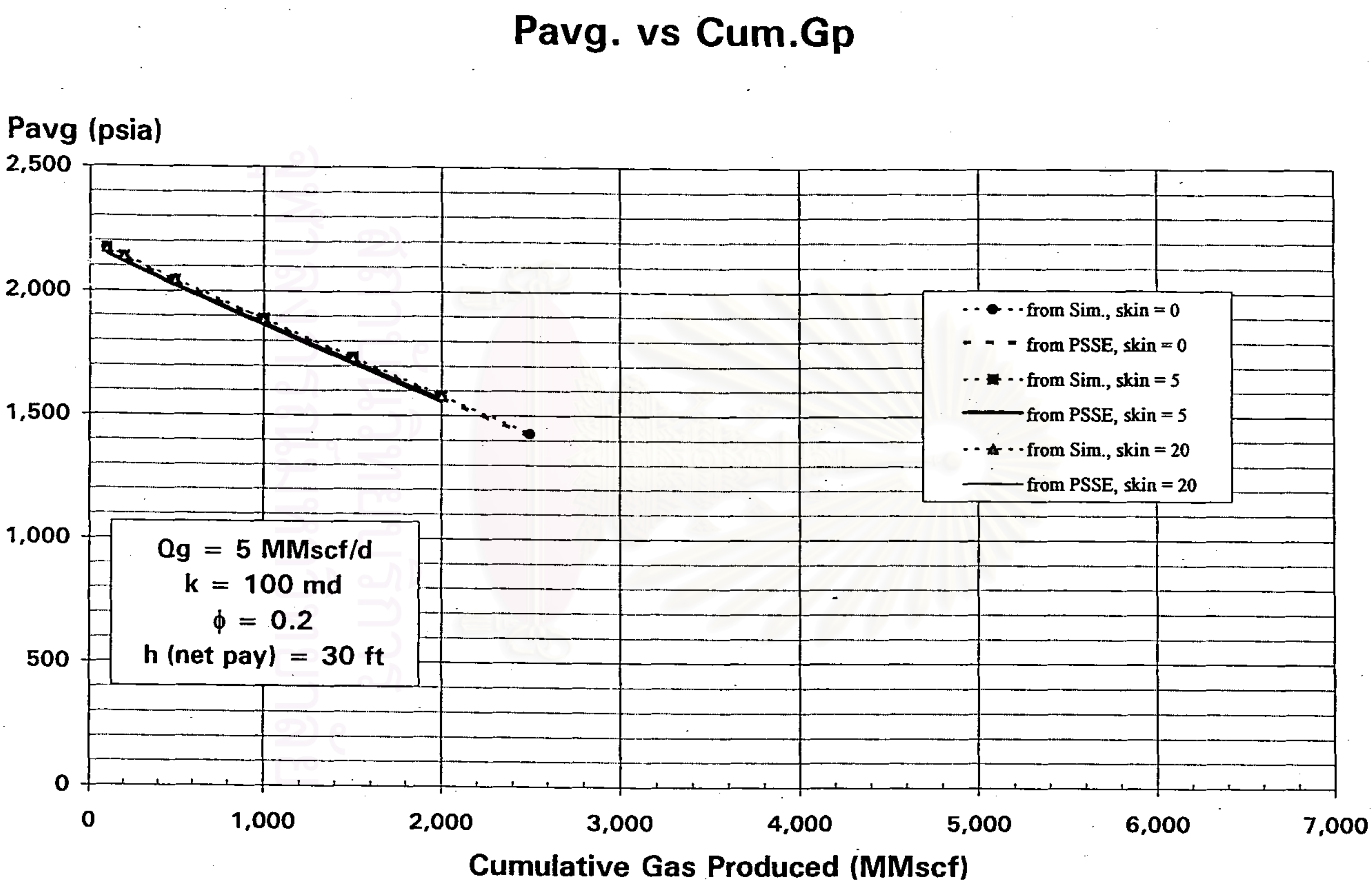

Figure 6-21 Average reservoir pressure as a function of cumulative production (different skin values, q_g = 5 MMscf/d)

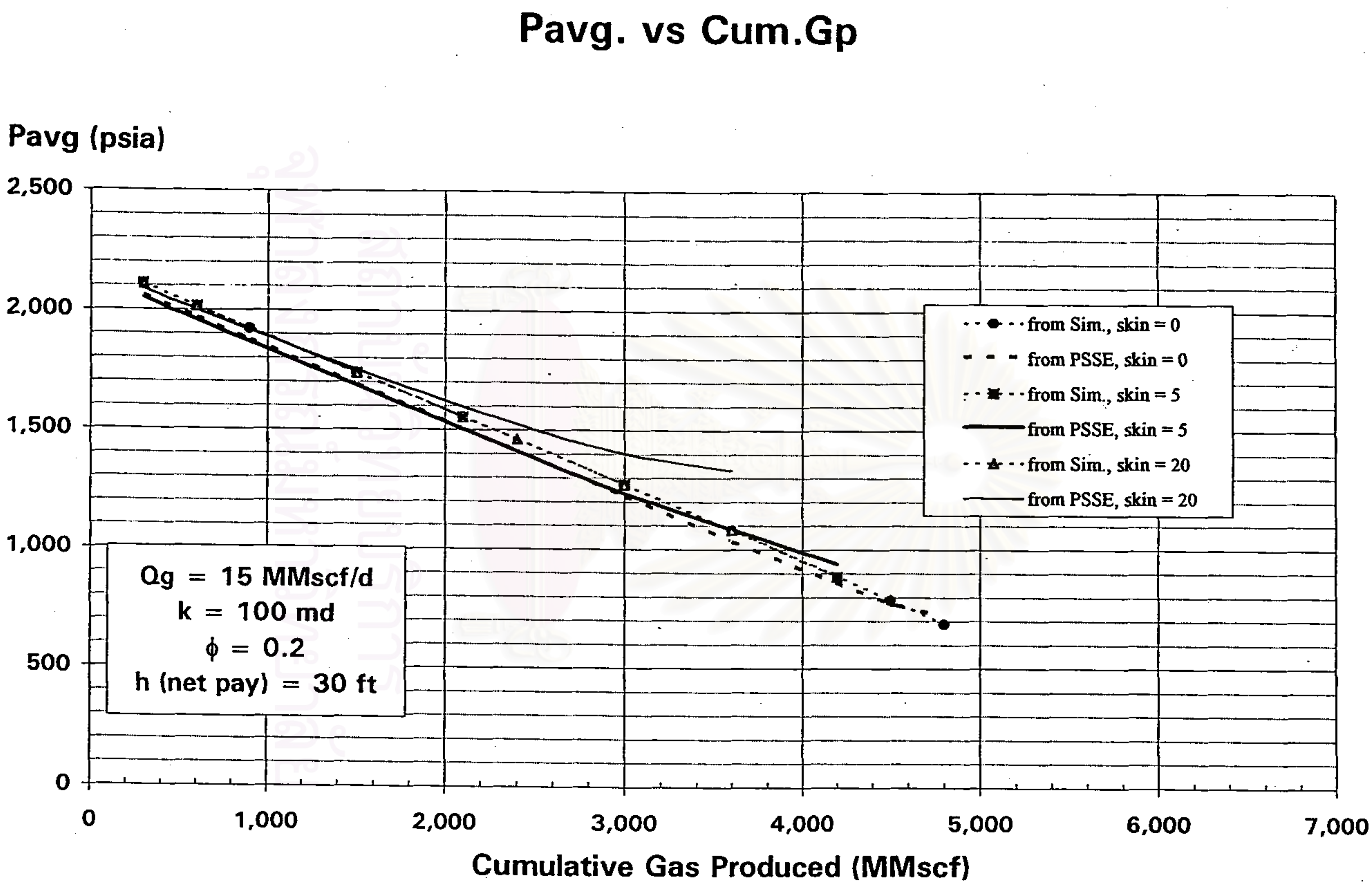

Figure 6-22 Average reservoir pressure as a function of cumulative production (different skin values, q_g = 15 MMscf/d)

differently from that predicted by the pseudo-steady state equation. This results in wrong $\bar{p}$ and hence wrong practical GIIP. However, from the results obtained in this study, the effect of skin will be significant only when gas flow rate is sufficiently high.

6.8 Single-layered reservoir with two production wells

For the case of single-layered reservoir with two wells, each of the two wells is assigned to be located symmetrically to the other, and produces at the same constant rate. For this case, the study was carried out in the way to evaluate the GIIP of the whole layer (whole system). To evaluate the GIIP of the whole layer, in this study, two different methods were applied: (1) separated-well and (2) combined-well.

1. The separated-well method is the method that the drainage area (or drainage volume) of each well is separately studied. As it is known that under pseudo-steady state condition the ratio of the drainage volume of any well in the system to the total volume of that system is proportional to the flow rate of that well to the summation of the flow rate of each well in the system. If the assigned flow rates to both of the two wells are equal, the drainage volumes of the two wells will be also equal. $\bar{p}$ of each drainage volume was calculated from both the simulator (actual $\bar{p}$) and the pseudo-steady state equation (practical $\bar{p}$). The $\bar{p}$ obtained from the simulator is, in fact, a $\bar{p}$ of the layer. Therefore, for the case of a single-layered reservoir with two wells given in this study in which the productions of the two wells were started at the same time and the same constant flow rate was assigned to each of the two wells (hence the same

drainage volume of the two wells), $\bar{p}$'s from the simulator (actual $\bar{p}$) for the two drainage volumes at any time of the production period are the same (and equal to the $\bar{p}$ of the whole layer). $\bar{p}$'s from the pseudo-steady state equation for the two drainage volumes are separately calculated. After the $\bar{p}$'s from both the simulator and the pseudo-steady state equation were obtained, the z-factor values corresponding to those $\bar{p}$ were determined from the equation of Dranchuk-Abou-Kassem. Then, sets of $\bar{p}$ and z-factor data of each drainage volume were used to construct p/z plots for each drainage volume From the p/z plot of each drainage volume, the material-balance and practical GIIP's of each drainage volume could be obtained. Due to the constant flow rate of the two wells, the fictitious boundary of each drainage volume would not change, hence the constant volume of the drainage volume of each well. Therefore, the summation of the drainage volume of each well should be equal to the total volume of the whole system (of the whole layer).

2. The combined-well method is the method that the two wells are considered to be as a fictitious well located at the center of the layer. In other words, it can be said that the combined-well method will transform a single-layered reservoir with two wells to be a single-layered reservoir with one fictitious well. The gas flow rate of the fictitious well will be the total flow rate of the two wells. In this study, after the single-layered reservoir with two wells was transformed, $\bar{p}$ of the layer was still calculated from both the simulator and the pseudo-steady state equation. Similar to what were done in the previous studies, for this case, the p_{wf} obtained from the simulator (actual p_{wf}) was still needed for the pseudo-steady state equation to calculate $\bar{p}$ of the layer.

For this combined-well method, after sets of $\bar{p}$ (from both the simulator and the pseudo-steady state equation) and z-factor data were obtained, p/z plots were also prepared for both cases of using $\bar{p}$ from the simulator and from the pseudo-steady state equation.

For the case of a single-layered reservoir with two wells used in this study, the permeability of the layer is 100 md, while the flow rate of each of the two wells is constant at 7.5 MMscf/d. The results from the study are shown in Table 6-8.

Table 6-8 Comparison of results from the separated-well and combined-well methods.

Method	GIIP (MMscf)			Error of GIIP from a P/Z plot (%)	
	actual	MB	practical	Using Pavg from Sim.	Using Pavg from PSSE
separated-well	6,674	6,822	6,084	+2.2	-8.8
combined-well	6,674	6,796	6,834	+1.8	+2.4

The differences of the two different methods can also be shown in Figures 6-23 to 6-25 in terms of $\bar{p}$ (plots of $\bar{p}$ vs. Gp) and GIIP (a p/z plot).

From Table 6-8, the errors of the material-balance GIIP's obtained from both of the two different methods (separated-well, and combined-well) are small and can be considered to be within the same range (+2.2% for the separated-well method, and +1.8% for the combined-well method). While, the errors of the practical GIIP's obtained from the two different methods are quite different (-8.8% for the separated-well method, and +2.4% for the combined-well method). One explanations for this difference is that a suitable shape factor, C_A , could not be achieved for the case that the separated-well method was applied. (C_A used in the study (in the pseudo-steady

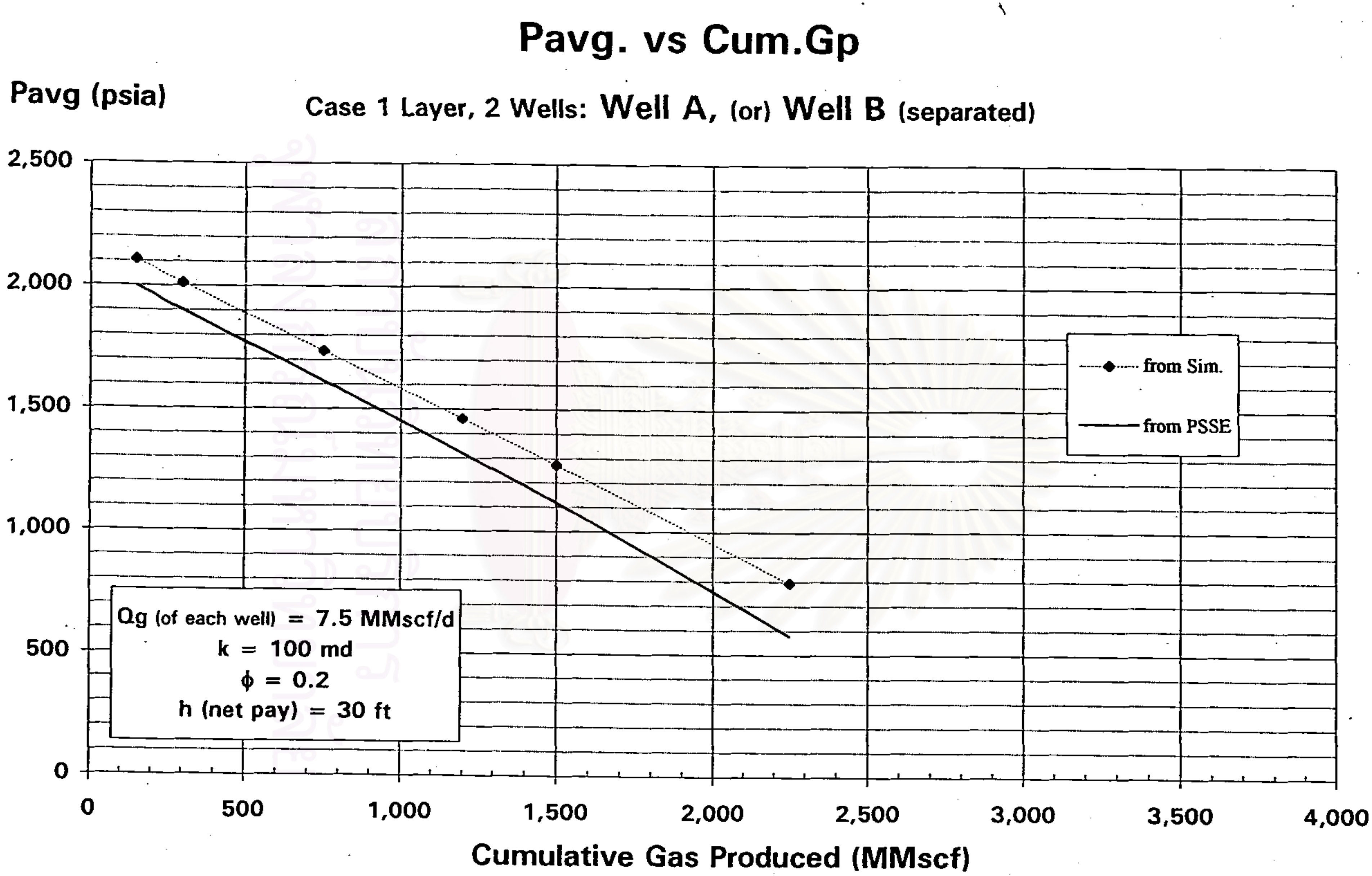

Figure 6-23 Average reservoir pressure as a function of cumulative production for a one-layer-with-two-wells system (separated-well method)

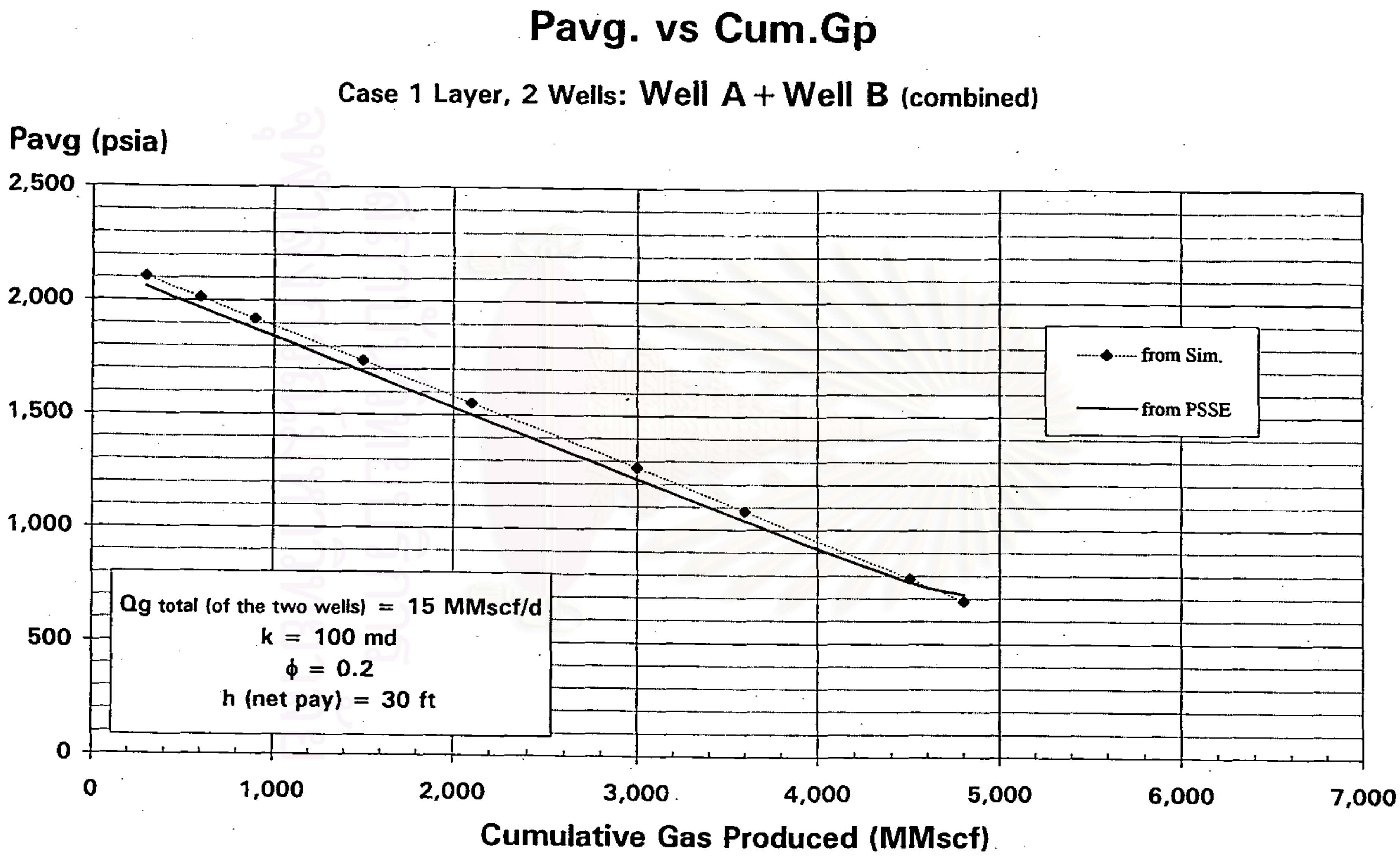

Figure 6-24 Average reservoir pressure as a function of cumulative production, 1 layer with two wells (combined-well method)

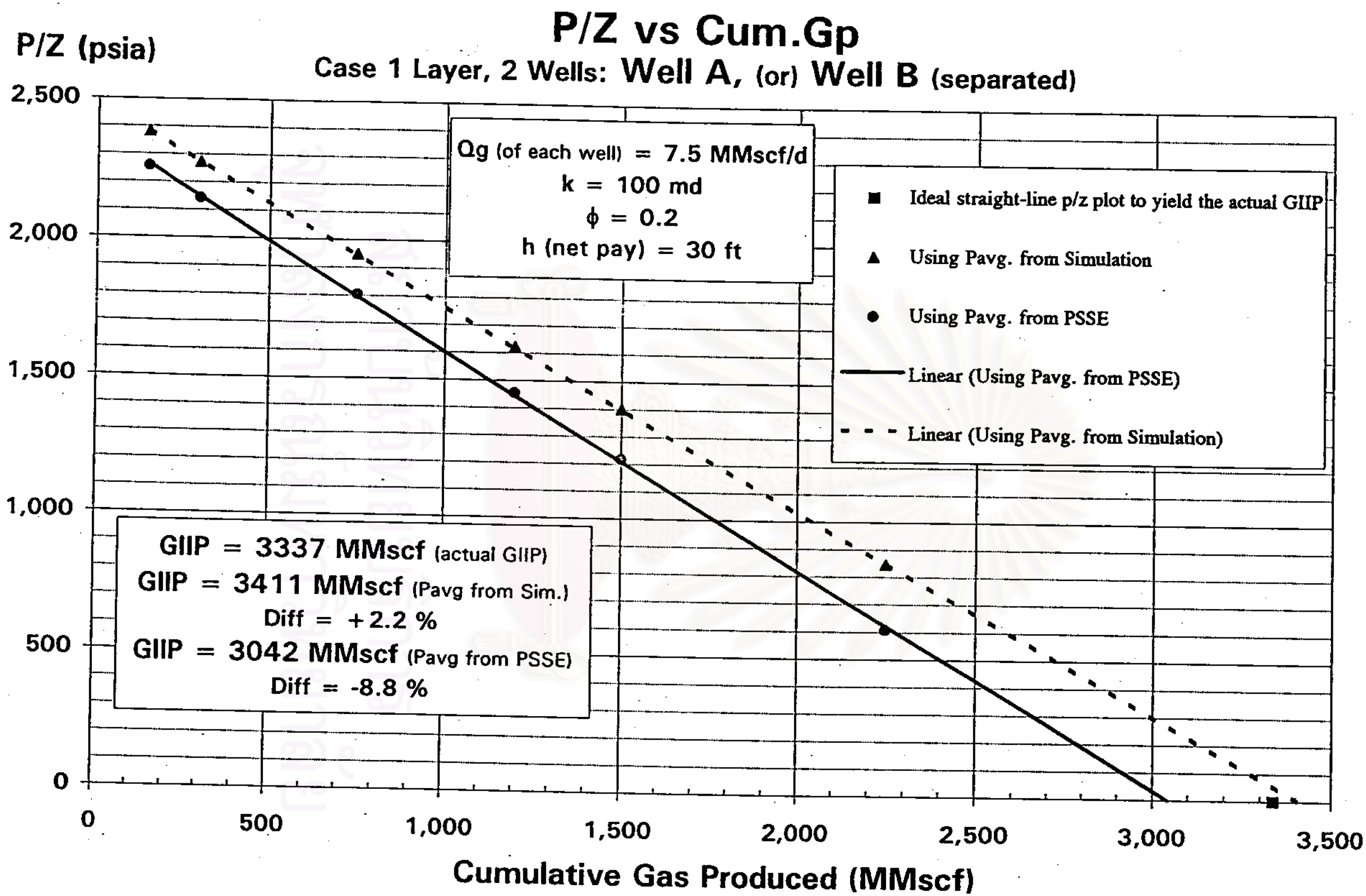

Figure 6-25 The p/z plot of a one-layer-with-two-wells system (separated-well method)

state equation) does not exactly represent the correct C_A for the simulation model.)

However, to evaluate the GIIP for the case of a single-layered reservoir with two wells similar to this case study, if good estimate of $\overline{p}$ of the layer is available and the production rates of the two wells are mainly not constant, it is suggested that the combined-well method should be used because this method is not only simpler (than the separated-well method for such a case), but also can give an acceptable value of the GIIP.